DISSERTATION

Co-simulation based Smart Grid Communication Infrastructure Analysis

Submitted at the Faculty of Electrical Engineering and Information Technology, Vienna University of Technology in partial fulfillment of the requirements for the degree of Doktor der technischen Wissenschaften (equals Ph.D.)

under supervision of

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Kurzfassung

Durch zunehmende Integration von Informations- und Kommunikationstechnologien (IKT) in elektrische Energiesysteme ist das intelligente Stromnetz zu einem großen Cyber-Physical System geworden, welches komplexe Interaktionen und Abhängigkeiten zwischen IKT und Energiesystem, aber innerhalb der Domänen aufweist. Die Verwendung eines domänenübergreifenden Modellierungsansatz ist notwendig, da es nicht mehr möglich ist, die einzelnen Teilbereiche unabhängig voneinander zu betrachten. Monolithische Ansätze hierfür sind wenig praktikabel aufgrund ihrer fehlenden Detailliertheit und Flexibilität. Eine attraktive Alternative ist Co-Simulation. Jedoch unterstützen nur wenige Werkzeuge diesen Ansatz aufgrund fehlender Interfaces für die native Kopplung von Simulationstools, um bidirektionale Kommunikation, weitreichende Automation, Monitoring und Regelung, selbstheilende Netze und Ansätze zur Vergrößerung der Aufnahmefähigkeit für erneuerbare Energien abzubilden.

Das Ziel dieser Dissertation ist die Erforschung und Entwicklung eines flexiblen, erweiterbaren und auf Co-Simulation basierenden Werkzeugs zur Analyse der Effekte von IKT-Integration in Stromsysteme. Das erarbeitete Werkzeug erlaubt eine genaue dynamische Simulation von Energieflüssen, Kommunikation und Regelung. Indem es etablierte und anwendungsspezifische Simulatoren verwendet, unterstützt es die Zusammenarbeit von Fachexperten aus den genannten Bereichen sowie die Nutzung vorhandener Modelle und Know-How. Dies erhöht die Zuverlässigkeit der Ergebnisse und reduziert den Aufwand der Systemmodellierung signifikant. Durch den Fokus der Arbeit auf generische Ansätze zur Simulatorkopplung ist die Integration weiterer Simulatoren wie auch realer Komponenten besonders einfach und schnell durchführbar. Die Anwendbarkeit der entwickelten Lösung wurde anhand dreier sehr unterschiedlicher Fallstudien unter Beweis gestellt, in denen verschieden Kommunikationssysteme, Technologien und Szenarien simuliert wurden. Die Auswirkungen unterschiedlicher Parameter in der Kommunikationsinfrastruktur auf die Performance von Regelungsalgorithmen konnten erfolgreich analysiert und anhand von Key Performance Indikatoren auf führenden EU-Projekten bewertet werden. Die gesammelten Ergebnisse zeigen einen nicht-linearen Zusammenhang zwischen der Performance des Stromnetzes und des Kommunikationssystems. Aufgrund seiner modularen Architektur erwies sich das entwickelte Werkzeug bereits in zwei laufenden EU-Projekten für ähnliche Fragestellungen als nützlich.

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Abstract

With the tight integration of computation and communication into the power system, the Smart Grid has become a large Cyber Physical System, with complex *cyber* and *physical*, *inter*- and *intra*-domain, interactions and interdependencies. A multi-domain modeling approach is, thus, required to be applied for the modeling of such systems, as it is no longer possible to model the participating domains independently. Monolithic approaches are not practical due to their lack of details and adaptability. An attractive alternative is co-simulation, but such tools/methods are not widely available due to scarcity of native coupling interfaces to analyze two-way communication, enhanced automation, monitoring and control, self healing capabilities, and increased hosting of renewable energy resources.

The aim of this dissertation is to investigate and develop a flexible, extendable and co-simulation based tool-set for analyzing emerging behaviors and resulting effects of power systems with tight integration of communications and controls. Such a tool-set is developed, capable of providing fine-grained and detailed dynamical simulation of power, communication and control systems. By utilizing well-known, domain specific and specialized tools, it enables collaborations and makes it possible to reuse existing models and know-how, improving the reliability and reducing the efforts, considerably. Due to a strong focus on development of generic coupling interfaces, the tool-set enables easy integration of many other tools, enabling rapid adaption and making the tool-set highly applicable in many areas of Smart Grid design and analysis. The usability and applicability of the proposed tool-set has been demonstrated with three diverse case studies, where varying communication infrastructure models, technologies and scenarios are investigated. The tool-set show effects of different communication infrastructure parameters on the performance of the Smart Grid, using the key performance indicators from leading European Smart Grid research projects. Collected results identify a non-linear relationship between Smart Grid and communication infrastructure performance. Parts of the tool-set have been used and validated in two European research projects.

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First of all I would like to express my heartily gratitude to my supervisor and mentor Professor Peter Palensky. I am deeply indebted for his constant guidance, encouragements and tremendous support throughout my Ph.D. I truly feel lucky as he is exceptionally intelligent and always full of new ideas. He was always aware of my strengths and weaknesses and suggested me accordingly. He helped me in editing and confirming every aspect of research results. He has been friendly, caring, supportive and helpful in numerous ways for which I will never be able to say enough thanks.

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Jawad Haider Kazmi
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Table of Contents

Abbreviations

CPS	Cyber Physical System
CPES	Cyber Physical Energy System
SG	Smart Grid
PMU	Phasor Measurement Unit
ICT	Information and Communication Technology
GHG	Greenhouse Gas
WAN	Wide Area Network
LAN	Local Area Network
PLC	Powerline Communication
EV	Electrical Vehicle
EVSE	Electrical Vehicle Service Element
PV	Photovoltiac
FIPA	Foundation for Intelligent Physical Agents
OLTC	On Load Tap Change Transformer
API	Application Programming Interface
HEMS	Home Energy Management System
AMI	Advanced Meeting Infrastructure
TCP	Transmission Control Protocol
IP	Internet Protocol
KPI	Key Performance Indicator
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
MAS	Multi-agents System
FACTS	Flexible AC Transmission System
NIST	The National Institute of Standards and Technology
DER	Distributed Energy Resources
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
HLA	High Level Architecture
WAMC	Wide Area Monitoring and Control
IED	Intelligent Electrical Device
SGAuT	Smart Grid Application under Test
EMS	Energy Management System
DMS	Distribution Management System
CIM	Common Information Model
VMU	Voltage Measurement Unit
ISO	Independent System Operator
TSO	Transmission System Operator
DSO	Distribution System Operator

1 Introduction

1.1 Background and Motivation

The Electrical power system is one of the primary driver of the economic growth, and there has been a strong correlation between electricity availability and use, and quality of life [BGS13]. Electrical power system generates, manages and provides the electricity and it is considered to be one of "*the most complex machine ever built in human civilization*" [FK15]. In the beginning, electrical power system were developed as small direct current power generators for use, mainly, in factories and mines. The evolutionary process of modernization and development of electrical power system began soon after its birth [TA16]. Thomas Edison, in 1882, designed and installed Pearl Street Station, considered to be the first ever centralized direct current electrical power system. Electrical power system kept on evolving, supported by technology and drove by needs; from direct current to alternative current and from small single customer system to a huge system with many large centralized power generators, serving thousands of customers. For nearly a century, the passive model of power system operation remained largely unchanged; one-way communication where generated power, from large centralized power generators, was sent to customers through transmission and distribution lines [BJI16, CSF+16]. This passive mode of operation is gradually obsoleting due to many technological, economical, environmental and political factors.

Starting from 1950s, increased electricity demand in many developing countries resulted in a speedy expansion of electrical power system. Most of the equipment installed during that period had either completed its useful life or became outdated and needed to be replaced. Furthermore, the overhead line circuits installed had reached its electrical capacity and thermal constrains. All such equipment needed to be replaced but a mere replacement would not be a viable option. This provided an opportunity for the modernization of power system with innovative equipment, designs and practices. Furthermore, major blackouts, for example, the Northeast blackout of August 14, 2003 in United States and Canada [239], the blackout in southern Sweden and eastern Denmark of September 23, 2003 [LE04], September 28, 2003 blackout in Italy [238], along with some events due to severe weather conditions, paved the way towards realization of the need for a more intelligent, automated and resilient power grid [ELW+12, ADF+05, BJI16].

From the beginning of the 21st Century, greenhouse gas emissions due to the traditional power generation methods using fossil fuels, raised serious environmental concerns. This triggered world-wide research efforts for finding clean and green power generation methods that have low CO_2 footprints. Although, power generation from nuclear and hydroelectric sources have very little contribution to green house gas emissions, but their large scale expansion are constraint due to high capital cost, safety concerns and limited number of sites. The focus, thus, has been on the development of renewable energy sources including wind, solar, geothermal, small hydro, biomass and biogas, combined heat and power, and fuel cells etc. [BDT14].

Increased hosting of the "green and clean" distributed energy resources (DERs) into the electrical power system contributes not only towards decreasing the environmental effects but also increases flexibility and reliability of the power system. On the other hand, this has brought many technological challenges due to the intermittent nature and the problem in accurate generation forecasts for these resources, leading to power quality and reliability issues [SAK+15].

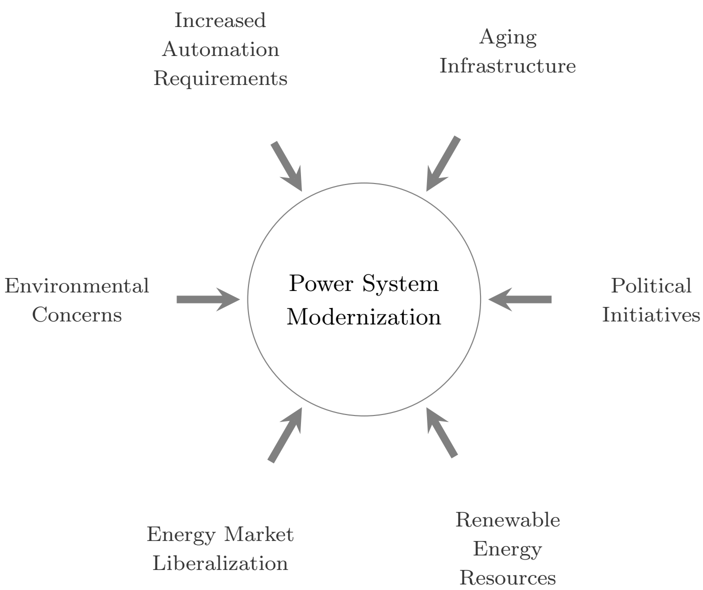

Figure 1.1: Some major motivating factor towards power system modernization [ELW+12].

It was realized that integration of information and communication technology and control with the electrical power system could provide enhanced monitoring and control, and automation. This could result in efficient energy management systems with increased reliability and availability. All these factors (Figure 1.1) in addition to national and regional initiatives such as EU Vision 2020 (EU SmartGrids Framework) [Che07, Bie13] and some others [LT14, LRH16] initiatives worldwide further motivated the need for modernization of power system.

Motivated by these and many others, technological, environmental and political factors, the ongoing modernization of the power system is set forth by the vision of *Smart Grid*. The vision of Smart Grid is considered to be the future of the power system [Li14] and is expected to address many challenges that the tradition power systems have been facing. Since, there is no unified definition of the Smart Grid, it is only possible to describe it with a set of objectives and capabilities [BDT14]. The Smart Grid has been aiming for a power system that is more situation aware, automated, economic, resilient, reliable, and environment friendly. To achieve these aims, it integrates information and communication technology, control, and the innovative power electronics into the power system to enable two-way communication, enhanced automation, monitoring and control, self healing capabilities, and increased hosting of renewable energy resources. It further enables massive and efficient deployment, and use of distributed energy resources and storage, provides sustainable power delivery with efficiency, enables distributed nature of network management, improved assets efficiency and utilization, and last but not least, provides the support for electrification of transportation system [GWP+14, CSF+16, FK15]. The U.S. Department of Energy has identified seven major characteristics of the Smart Grid [234], summarized and presented in Figure 1.2.

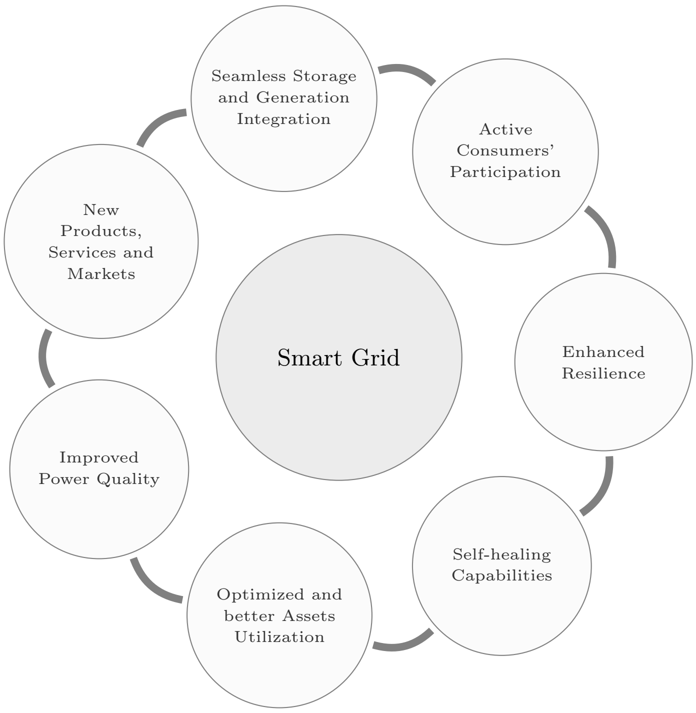

Figure 1.2: Seven characteristics of Smart Grid, as identified by U.S. Department of Energy [234].

The research efforts on different aspects of the Smart Grid has increased many folds during the last couple of years. According to Colak *et al.* [CFS+15], a total of € 3.13 billion had been invested till 2014 in Europe alone on Smart Grid projects. Furthermore, a potential investment of € 51 billion, in Europe, is projected due to smart meter installations by 2020 in [FHH09]. Since, Smart Grid will be critical and expensive systems therefore, they needed to be designed with precision from the very beginning [FK15].

The term Smart Grid has been extensively used for describing modernization of power system, during last couple of years. Due to a generalization of concepts and lack of unified understanding, Smart Grid means different things for different groups of people. Due to this diversity in views, some more specific terms such as “Power System ICT & Control” and “Power System Digitization” are now, sometimes, used to described power system modernization.

1.2 Statement of Problem

Although, the electrical power system is using communication technologies for support in its operations since 1970s, but these methods have not changed much until recently. The electrical power system has been undergoing a transformation under the vision of Smart Grid where strong focus is laid on the integration of information and communication technologies, innovative power electronics and control in power system [BGS13].

Communication infrastructure is being considered as the nervous system of the Smart Grid. It is believed that by integrating information and communication layer over power system would not only improves power system efficiency and reliability, but, further, could reduce the green house gas emission up to 21%. Communication infrastructures are used, for example, to connect sensor and actuators in the power system and are used to carry important, real-time, system state information to controllers and control actions to actuators. They also provide price information to be used for demand response applications [KS08, BGS13]. To provide such capabilities, it is the critical requirement to develop a communication infrastructure that not only connects divers equipment but is reliable and fulfills the requirements of Smart Grid applications and services [YQST13].

The Smart Grid is a multi-domain system with tightly integrated power (*physical*), communication and control (*cyber*) domains. The domains have complex *inter*- and *intra*-domain *interactions* and *interdependencies* (Figure 1.3). These interactions and interdependencies, being unique, resulting in new behaviors and effects; making it less appropriate to model these domains independently while ignoring their interactions and interdependencies [Lee10].

This presents numerous challenges to domain experts involved in the Smart Grid development. Most of the state-of-the-art modeling approaches and simulation tools are incapable of capturing the emerging behaviors and effects (due to interactions and interdependencies of *cyber* and *physical* sub-systems), as these approaches and/or tools where not designed for such systems. This requires that a multi-domain approach to be applied for the Smart Grid analysis [Lee08, BCG12, PWE14, KM15, MGN^{+}16].

To overcome these shortcomings of exiting tools and methodologies for the analysis of the Smart Grids, new and improved tools and methodologies are required. This dissertation intends to provide such a tool-set for the study of emerging behaviors and effects.

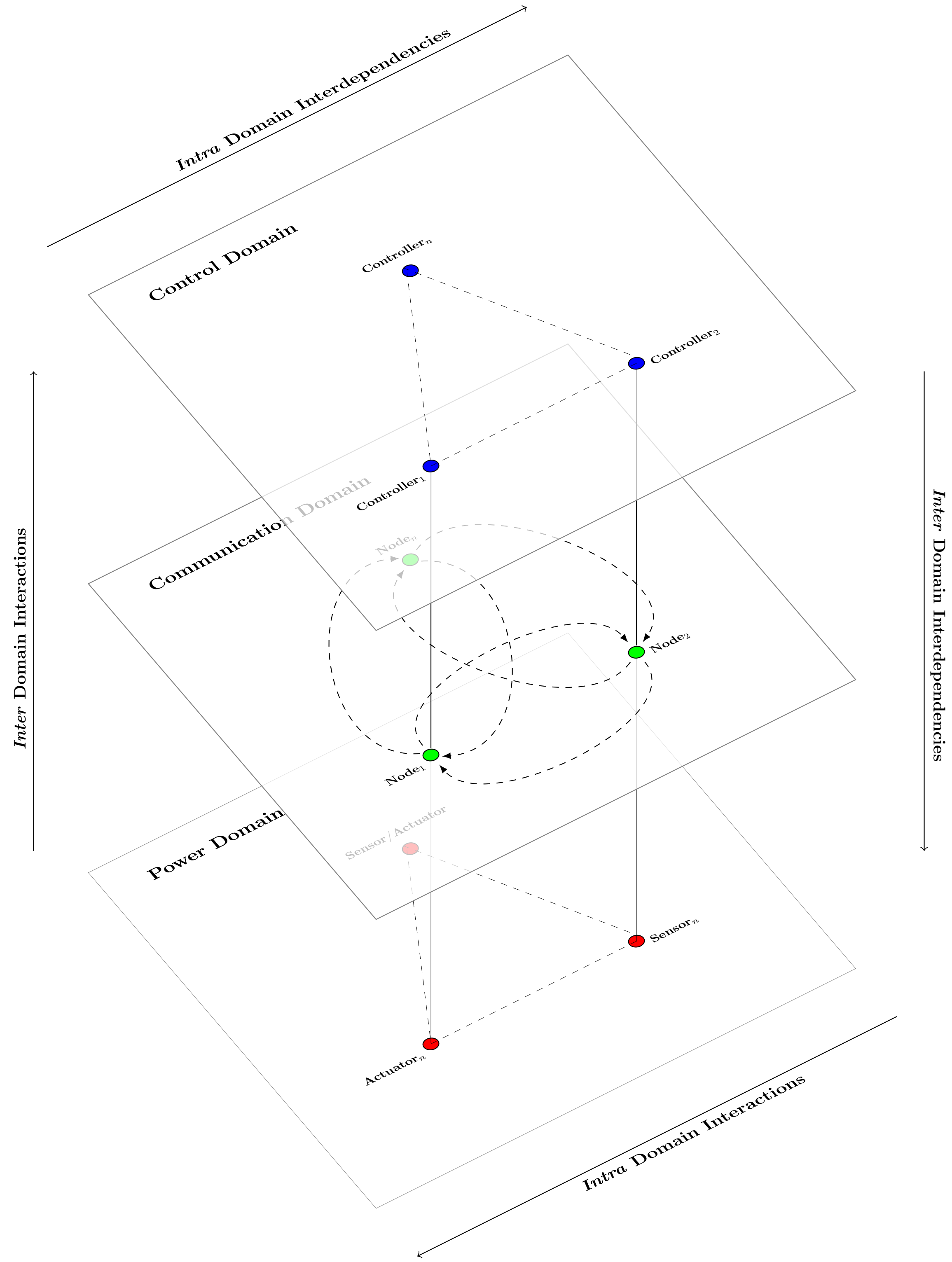

Figure 1.3: The Smart Grid is a multi-domain system where the domains have complex *inter-* and *intra-*domain, *interactions* and *interdependencies*. This makes multi-domain modeling and simulation approaches, for Smart Grid analysis, a realistic approach.

1.3 Aim, Goal and Scope

The aim of this dissertation is to investigate and develop a tool-set to analyze the effects and emerging behaviors due to the integration of information and communication technology, and control into the power systems. Such analysis is helpful in identifying suitable communication infrastructure models and parameters, fulfilling the requirements of a Smart Grid application and/or service. It is, further, expected to permit the quantification of performance, measured during simulation of communication scenarios with varying parameters.

The Smart Grid is transforming the power systems at generation, transmission and distribution levels. There is sparse control available at distribution grid levels today [MOD14], enabling a wide range of possible Smart Grid applications. The case studies in this dissertation are, therefore, focused mainly at low voltage and medium voltage distribution levels.

The research question addressed in this dissertation is thus formulated as:

> How do communication infrastructure parameters affect Smart Grid performance and what indicators could be used to measure it?

Answering this question will further allow us to address questions such as:

(a) What communication infrastructure would be suitable for a specific Smart Grid solution? How can its performance be evaluated under different conditions?

(b) To what degree a communication infrastructure is able to satisfy the requirements of a certain Smart Grid application?

(c) How communication characteristics and/or parameters such as e.g. bandwidth, protocols, latency, failures, cyber attacks etc. could affect the monitoring and control operations in Smart Grid?

However, answer to the research question, depends on following two intermediate questions:

1. What methods exists for analyzing this influence? How effective is the co-simulation based methodology in terms of:
   (a) implementation efforts,
   (b) suitability for inter-disciplinary modeling, for domain experts from power system, controls, and communication?
2. What is an extendable co-simulation design to enable versatile communication case studies for a range of the Smart Grid applications with different tools and interfaces?

1.4 Expected Results and Challenges

The intended outcome is a tool-set that would enable the quantification of the influence of varying communication infrastructure models on the Smart Grid performance. This would further enable various Smart Grid innovative solutions to be analyzed with respect to diverse communication infrastructure models. The tool-set will enable detailed and fine-grained dynamical simulation for large coverage of the Smart Grid case studies. Varying types of control applications, power system analysis time scales and communication infrastructure modeling with popular communication technologies and scenarios can be investigated. It will aid in planning, analyzing and validating communication infrastructure model with the power systems and the control strategies, providing support for a large community of the Smart Grid domain experts.

The Smart Grid simulation is a multi-domain and complex topic with continuous and discrete dynamics. Due to lack of native tools and interfaces for coupling simulators, custom interfaces and tools are needed. Integrating these custom components into exiting tools is a further complex task, requires handling interoperability, architectural mismatches, information and data flow methods and capabilities etc.

1.5 Dissertation Overview

The rest of the dissertation consists of eight further chapters, logically divided into three parts (Figure 1.4).

The first part (Chapter 2 & 3), presents the context of study and a review of literature related to modeling and simulation of the Smart Grid. Chapter 2, describes the transformation of the power systems towards the Smart Grid along with motivating technological, environmental, economical and political factors. Since, the Smart Grid has no unified definition, numerous definitions, meanings and understandings are provided along with some common objectives. Communication is an important enabling technology and is considered to be the nervous system of the Smart Grid. Its role, reference models, usages and importance is highlighted. The Chapter 3 presents the analysis of literature for modeling and simulation of the Smart Grid.

The second part (Chapter 4, 5, 6 & 7), presents the proposed co-simulation-based methodology and then its application on three case studies. Chapter 4, describes the whole and then individual *parts* of the proposed methodology. Chapter 5, presents the first case study related to communication infrastructure analysis of a low voltage power system modeled with an embedded control for voltage regulations when the network hosts many photovoltiac systems and electrical vehicle. Chapter 6, presents the second case study describing an innovative Smart Grid application for a low voltage rural distribution network with an active power curtailment based coordinated controller with a network having many distributed generators. While, Chapter 7, describes the interfaces, models and communication infrastructure analysis with proposed tool-set for medium voltage power network with a distributed coordinated controller.

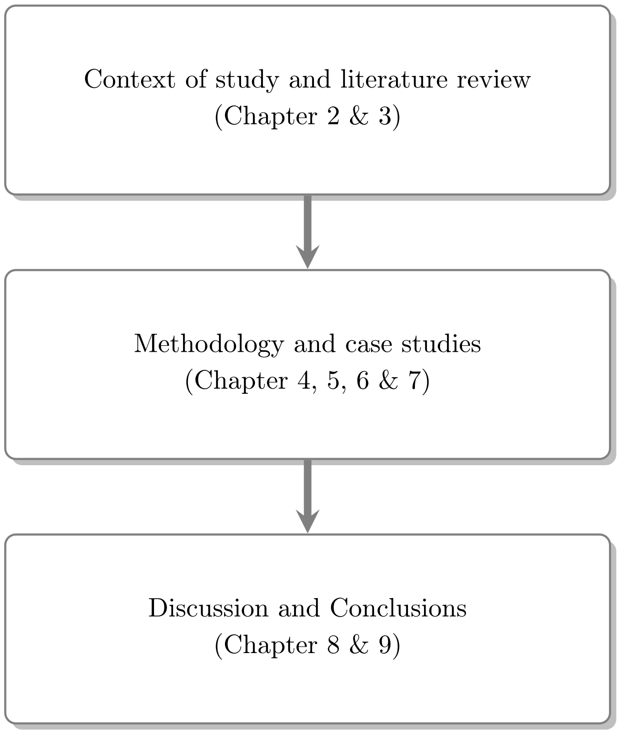

Figure 1.4: Three main parts of dissertation.

The third and final part (Chapter 8 & 9), presents the discussions on results and conclusion from this work.

2 Power System Transformation

This chapter presents a summary of the transformation of electrical power system, from its early days as small DC power generators to an advanced, smart and intelligent power system, now termed as the "Smart Grid". The chapter begins with a quick recap of electrical power system's history with some major events highlighted in Section 2.1. An introduction to the Smart Grid, including it components, benefits and applications etc., follows in Section 2.2. Section 2.3 draws up the use and importance of communication in the Smart Grid. The chapter concludes with a summary in Section 2.4.

2.1 Introduction

Early power system started as small direct current (DC) power generators designed mainly to be sold for industrial and mining usage. In 1882, Thomas Edison installed the first ever central electric DC power plant "Pearl Street Station", with 82 customers, in Manhattan, New York City. Low voltage levels and losses were the main reasons that DC power plants could only serve customers at short distances. Soon, these drawbacks were overcome with the invention of transformer and induction motor. This made the alternating current (AC) power systems more feasible as they could transmit power to relatively long distances [BJI16]. The complexity of power system kept on increasing, to meet the growing demand of electricity due to its social and economic role in society. Power system ultimately became one of "*the most complex machine ever built in human civilization*" [FK15].

In 1980s, efforts started around the world for energy market liberalization, aiming at reduced government role as the only utility provider and with increase private participation to make it more efficient, cost effective and competitive. To effectively manage the competitive market for a fair trade, concepts such as independent system operator (ISO) [Hog98], pool, bilateral and centralized electricity trading markets [SHP98] were introduced. In Europe, the energy policy, Green Paper in 1995, followed by European Parliament's Directive 96/92/EC in 1996, and Lisbon Strategy in 2000, contributed a lot for the establishment of a liberal energy market [KK11].

Increased awareness about long term environmental impact of power generation from fossil fuels raised serious concerns. A recent report [IEA15] from the International Energy Agency (IEA) shows (Figure 2.1) that the electricity consumption from 1973 to 2013 has increase up to fourfold, from $6,131$ to $23,322$ TWh, and has contributed considerably to an increase in green house gas emissions. Kruse *et al.* [KS08] claims that electricity generation has contributed 24% of global green house gas emissions in 2002 and further projected that it could be responsible for 14.26 $GtCO_2e$[1] in 2020. They have further, identified that ICT and the Smart Grid initiatives could reduce the green house gas emissions up to 21%.

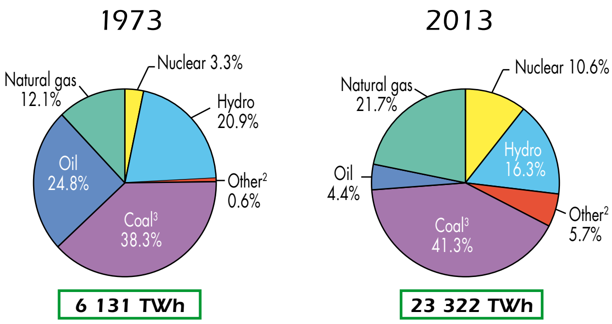

Figure 2.1: Electricity generation worldwide. Electricity generation has increased by fourfold from 1973 to 2013. In these graphs, electricity generation from pumped storage is excluded while geothermal, solar, wind, heat, etc. are included. Peat and oil shares are aggregated with coal.
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From the beginning of 21st Century, worldwide efforts for reduction of greenhouse gas emissions and finding 'clean' energy resources, started taking pace. Although, power generation from nuclear and hydroelectric sources have very little contribution to green house gas emissions, but their large scale expansions are limited due to high capital cost, safety concerns and limited number of sites. The focus, thus, has been on the development of renewable energy resources including wind, solar, geothermal, small hydro, biomass and biogas, fuel cells, combined heat and power, and electric vehicles [BDT14].

After reviewing the findings of 79 studies on green house gas emissions for different power generation methods, Amponsah *et al.* [ATK$^+$14] presents an estimated summary as shown in Figure 2.2. The estimates show that renewable energy methods (solar, wind etc.) have very low green house gas emissions contribution as compared to the methods based on fossil fuels.

Due to inherent nature of large variations in power generation in short time, increased penetration of renewable energy sources put ample effects on security of supply. Furthermore, major blackouts, for example, the Northeast blackout of August 14, 2003 in United States and Canada [239], the blackout in southern Sweden and eastern Denmark of September 23, 2003 [LE04], September 28, 2003 blackout in Italy [238], along with some events due to severe weather conditions, paved the

[1] gigatons equivalent carbon dioxide

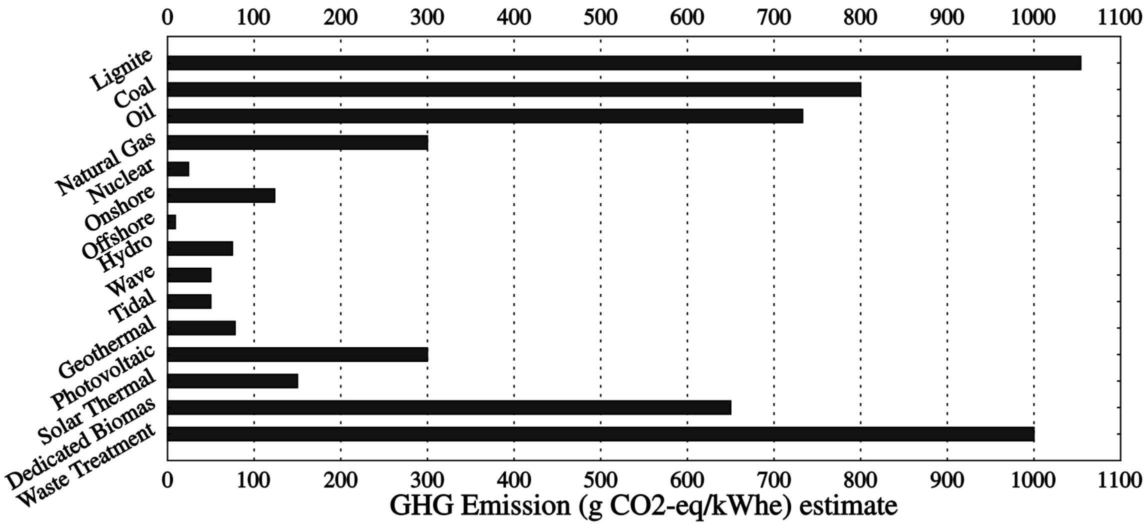


Figure 2.2: Maximum Green house gas emission estimates for different methods of electricity generation [ATK+14]. Methods using renewable energy source (wave, geothermal, photovoltaic etc.) produce comparatively low green house gas emission than from methods based on fossil fuels (coal, lignite etc.)

way towards realization of the need for a more intelligent, automated and resilient power grid [ADF+05, BJI16].

The development in power electronics, modern sensing & measurements, control technologies along with considerable progress in information and communication technology has been a significant factor in the transformation of the power system.

Modernization of the power system is an evolutionary process, since its birth [TA16]. A snapshot of this evolution is depicted in Figure 2.3. The need for a modern and intelligent power grid has long been identified even before the Smart Grid's inception. Ref [243] has identified five earliest works published in IEEEXplore; one of them being as old as 1997.

Motivating for the need of a *smarter grid*, Amin *et al.* [AW05] identifies the following *grand challenges*:

- large gap between transmission system capacity and projected loads,
- long distance transmission challenges due to market liberalization,
- needs for better situation awareness and control,
- centralized and decentralized control coordination.

A power grid of future has to fulfill many operational and planning needs to cope with the changing policies and demands. Banerjee *et al.* [BJI16] summarizes some of these requirements as:

- bi-directional power flow capabilities,

- resilience to natural disasters,
- highly reliable and available,
- capable of real-time dispatch and unit commitment decisions,
- ensure security of supply even when accommodate large share of generation from distributed renewable resources,
- meet the demands of multiple stakeholders in energy trade,
- enhanced risk assessment capabilities for outages and other financial risks,
- secure, reliable, available, resilient and cost effective,
- better situation awareness and fully automated with increased monitoring and control capabilities,
- coordinate the needs of all stakeholders.

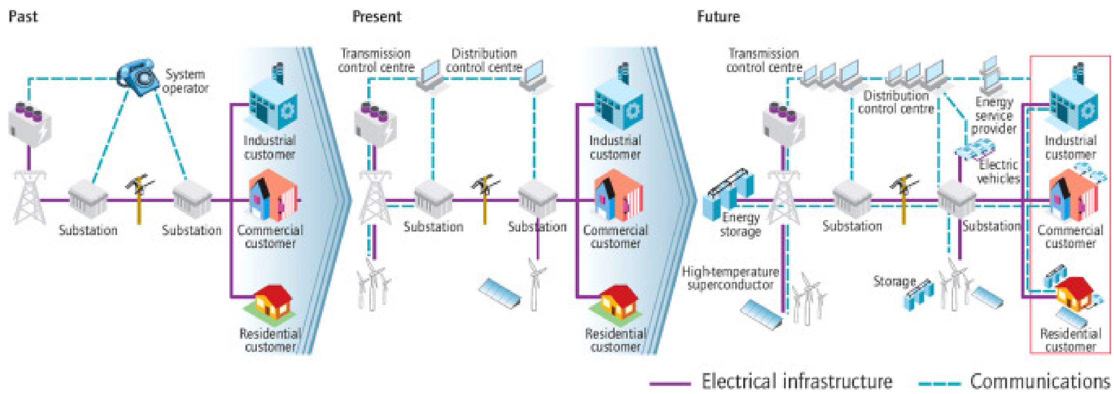


Figure 2.3: Evolutionary process towards a future power system for the delivery of green, reliable and resilient power system *Smart Grid*.
Reprinted from [CSF+16] with permission from Elsevier. Copyrights © 2016 Elsevier Ltd.

2.2 Smart Grid

The vision of *Smart Grid* is considered to be the future of the power system [Li14]. It is the modernization of power system with advanced real-time monitoring and control, integration of renewable distributed energy resources, two-way communication, self-healing capabilities, wherever required. It aims at making the traditional power system more resilient and reliable to ensure a stable power delivery to end users [CSF+16, FK15].

Mah *et al.* [MHLB14] recognizes two major factors by which the Smart Grid can be regarded as a *smarter* power systems. First is the ability to have two-way communication and electricity flow while the second is the integration of wide range of heterogeneous energy resource and services.

The Smart Grid is also expected to provide solutions to the challenges that utility companies around the globe are trying to overcome. Some of these challenges are liberalization of energy markets, the regulatory restriction on greenhouse gas emissions due to environmental concerns, automated demand response, energy conservation etc. [MC14].

Rest of this section presents some definitions for the Smart Grid, then important conceptual and reference model follows. Motivation for the Smart Grid vision are discussed next. Later on, a comparison and contrast of the differences between the traditional power systems and the Smart Grids are presented. Components, benefits for consumers, it technology areas and application, worldwide initiatives and standardization efforts follows.

2.2.1 Definitions

There is no unified definition for Smart Grid but rather several Smart Grid definitions exists in various initiatives, roadmap, literature and in the standards. One of the reasons for this diversity could be due to approaching it with different focus or view, while the other is broader scope. This causes different meanings of Smart Grid to different groups of people [BDT14].

According to European Technology Platform [Sma10], Smart Grid is:

> *"an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both-in order to efficiently deliver sustainable, economic and secure electricity supplies"*

While, United States Department of Energy (US DoE) [DOE09] defines Smart Grid as:

> *"smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources."*

Whereas, US National Institute of Standards and Technology (NIST) [AD09] sees Smart Grid as:

> *"The term 'Smart Grid' refers to a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices."*

In the UK, The Smart Grid Forum [For14] set the vision of Smart Grid as:

> *"A smart electricity grid that develops to support an efficient, timely transition to a low carbon economy to help the UK meet its carbon reduction targets, ensure energy security and wider energy goals while minimising costs to consumers. In modernising*

our energy system, the smart grid will underpin flexible, efficient networks and create jobs, innovation and growth to 2020 and beyond. It will empower and incentivise consumers to manage their demand, adopt new technologies and minimise costs to their benefit and that of the electricity system as a whole."

Further, the Canadian Electricity Association [241] see Smart Grid as:

"a suite of information based applications made possible by increased automation of the electricity grid, as well as the underlying automation itself; this suite of technologies integrates the behaviour and actions of all connected supplies and loads through dispersed communication capabilities to deliver sustainable, economic and secure power supplies"

Furthermore, an example definition from literature [FK15]:

"a more naive power grid system evolving into a smarter one through sensing, communicating, applying intelligence, and executing control/feedback for adjusting dynamic changes in primary and renewable electricity supply and demand"

According to Budka *et al.* [BDT14], it is not possible to describe Smart Grid with a single definition but rather with a set of objectives. Taking this further, and ignoring the differences in definition, there are some common requirements, concepts and capabilities that are considered essential for any Smart Grid implementation [GWP+14]. Some of such objective and requirements, as identified by Greer *et al.* [GWP+14], are summarized below:

- massive and efficient deployment and use of distributed energy resources and storage including renewable energy resource integration,
- sustainable power delivery with efficiency,
- distributed nature of network management operations,
- increased use of information and communication technologies for automation and control,
- support for the electrification of transportation system.

Another paramount agreement is on the realization that a new and improved information and communication technology (ICT) is required and will be the *enabling technology* for any Smart Grid implementation [URB+10].

2.2.2 Characteristics

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) has identified seven major characteristics for Smart Grid after consulting with major stakeholders [234]. These characteristics are summarized below:

- Active consumer participation.
- Seamless storage and generation integration.
- New products, services and markets.
- Improved power quality.
- Optimized and better asset utilization.
- Self-healing capabilities.
- Enhanced resilience.

Furthermore, the U.S. Department of Energy further listed the following technologies as the fundamental drivers of the Smart Grid vision [234].

- Use of two-way integrated communications for connecting components.
- Through the Use of open architectures, realization of the real-time monitoring and control.
- Measurements and sensing technologies to assist in providing more accurate and faster response to system conditions.
- Advanced storage, power electronics and diagnostics component development with the application of the latest research.
- Development of advanced control methods for self-healing capabilities.
- Rich and comprehensive interfaces, and decision support systems for better grid management.

2.2.3 Conceptual Models

The National Institute of Standards and Technology (NIST) recommends a conceptual framework in its NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0 [GWP+14] for the realization of the Smart Grid vision. The roadmap divides the Smart Grid into seven domains. Across domains, different communication and electricity links exists for the operation of the Smart Grid.

Figure 2.4 presents a comparison between the NIST framework and CENELEC [206] Smart Grid reference models. Figure 2.4a depicts the NIST conceptual model while Figure 2.4b presents its version after extended to meet European needs by CENELEC. The reference model extends the NIST model by adding eighth domain "Distributed Energy Resources", renaming "Generation" to "Bulk Generation" and adding further links to the domains.

Operations

This domain represents the management (eg. control centers etc.) controlling the flow of electricity. 'Operations' interact all the other six domains, through the communication links, to accomplish its delegate, the smooth operations of electricity flow.

Market

This domain represents stakeholders in the electricity markets. It also interacts with other six domains (customer can also be power generators) for exchanges of data over communication links.

Service Provider

Organizations that are providing their services to consumers and utilities are represented with this domain. There interaction with six domains here is also pure data exchange.

Customer

This domain represents the three types of end user, commercial, industrial or residential. 'Customer' interact with five other domains for data exchange. Electrical flow link are with 'Distribution' domain for receiving electricity and with 'Generation' domain when 'Customer' feeds in the generated electricity.

Transmission

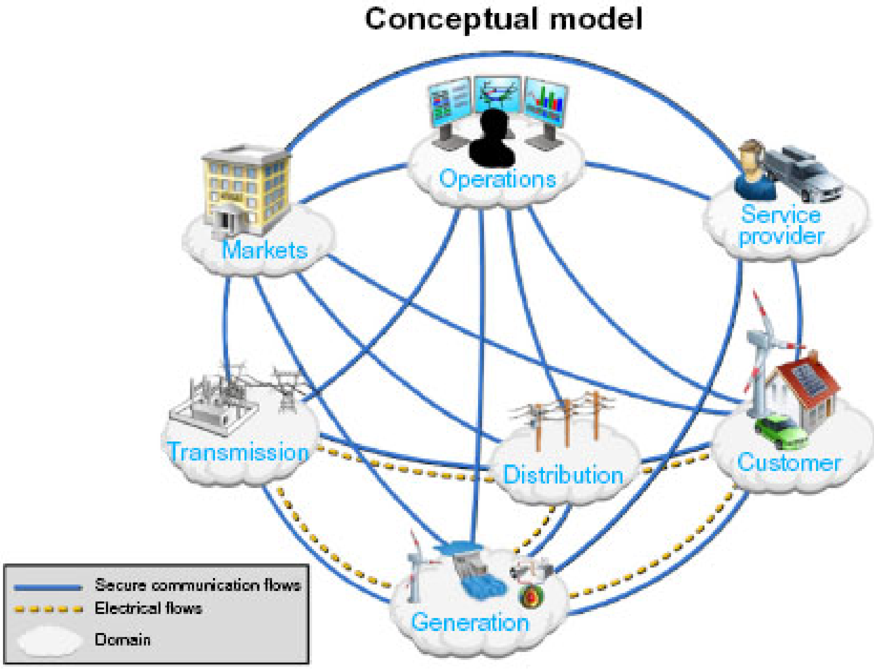
Entity responsible for carrying the electricity over long distances is represented by this domain. 'Transmission' interacts with four other domains over communication links while electrical flow exists with two other domains.

Distribution

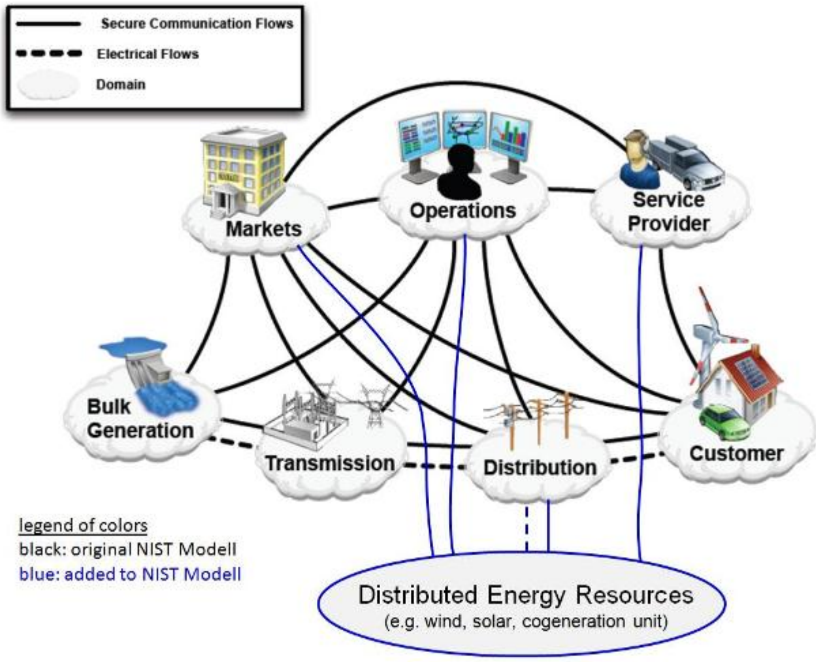
This domain represents the entity responsible for the distribution of electricity to customers. It has three electricity flow links and six communication links with other domains.

Generation

This domain represents the entities generating electricity. Major electricity (six) and communication flow (four) exists with other domains.



(a) The NIST Smart Grid Conceptual Model [GWP+14]. It identifies seven major domains in the Smart Grid. Through the identified links, these domains interact and coordinate.



(b) CENELEC extension of NIST Model [Sma12]. The reference model extends the NIST model by adding the eighth domain "Distributed Energy Resources", renaming "Generation" to "Bulk Generation" and adding further links to the domains.

Figure 2.4: The NIST Model along with its CENELEC EU extension.

2.2.4 Motivating Factors

In addition to realization of ICT as one of the enabling technology and the factor discussed in Section 2.1, Janaka *et al.* [ELW+12], noted some other factors that are having influence towards the power system transformation. Some of these factors can be summarized below. These factor further advocate the fact that power system transformation is a need base evolution.

Aging Infrastructure

Many developing countries saw a speedy expansion of the power system starting from 1950s to meet the growing demand. Most of the equipment, installed during that period, has either completed its useful life or is outdated. In both case, the only choice is to replace that aged equipment. In most cases, the stakeholders realized that a like-for-like substitution would not be an optimal choice. This provides an advisability for the modernization of power system with innovative equipments, designs and practices.

Capacity Limitations

Many of the overhead line circuits installed in last decades, had reached their capacities, in many countries of the world due to considerable increase in demand. In most cases, it is no longer possible to use these line for any further expansions such as integrating distributed renewable resources. In some case, the capacity expansion was delayed due to difficulty in meeting regulatory, administrative and/or legal issues. This further motivated the move towards modernization of power system.

Thermal and Operational constrains

As discussed above, due to reaching their capacity limits, the overhead lines and equipments were near their thermal limits as well. If more current is passed than the rated capacity, the result, in most cases, would be an increased probability of faults, reduced reliability and equipment life.

Power generation from renewable energy sources is inherently unpredictable. This results is fluctuating generation from these sources. Power system has to ensure the voltage and frequency in a regulatory band. Violating this could not only damage the customer or utility equipment but may result in (heavy) fines imposed by the regulatory body. Increasing capacity and overcoming the operational constraints is another factor that contributed towards power system modernization.

National Initiates

Many countries around the globe are adopting the Smart Grid as their national agenda. Many of these countries are considering the Smart Grid as a new commercial area for the development of innovative product and services. Some of these national initiatives are identified in Section 2.2.8 and 2.2.9.

2.2.5 Enhancements and Difference

Zhou *et al.* [ZHL+13] summarizes the three major enhancements brought in by the Smart Grid. Firstly the integration of renewable energy resources, secondly, near elimination of blackouts other than due to physical damages, and lastly, promotion of cost, consumption and emissions reductions.

Moreover, Hossain *et al.* [HOA13] put forwarded many enhancements that are due to the Smart Grid, in the traditional power system. These can be summarized as:

- reliability assurance, at the levels not possible before,
- capabilities for efficiencies and advancements in operations,
- help in reducing prices,
- consumer get more choices and information,
- provide heterogeneous energy sources integration.

Likewise, Tuballa *et al.* [TA16], compares and contrasts the major differences between tradition and future power system. This summary is presented in Table 2.1.

2.2.6 Benefits

The transformation of power system with integration of new and improved technologies, and designs for running innovative applications will bring many technical, economical and environmental benefits. Some of these benefits as identified by [FB14], can be summarized below:

Economic benefits

As the Smart Grid provides improved reliability which in turn will not only bring economic benefits for consumers but will improve the efficiency of business process and operations. Furthermore, smart energy management system and smart meters will provide capabilities for consumers to accurately monitoring their energy usages, enabling them to make informed decision and remain in the loop. Another benefit for consumers is the reduced cost of renewable energy resources such as roof-top photovoltiac systems, and possibility to feed excessive generation into a distribution system.

Table 2.1: The Smart Grid versus the traditional power system. Reprinted from [TA16] with permission from Elsevier. Copyrights © 2016 Elsevier Ltd.

Traditional Power System	Smart Grid
Mechanization	Digitization
One-way communication	Two-way real-time communication
Centralized power generation	Distributed power generation
Radial Network	Dispersed Network
Less data involved	Large volumes of data involved
Small number of sensors	Many sensors and monitors
Less or no automatic monitoring	Great automatic monitoring
Manual control and recovery	Automatic control and recovery
Less security and privacy concerns	Prone to security and privacy issues
Human attention to system disruptions	Adaptive protection
Simultaneous production and consumption of energy/electricity	Use of storage systems
Limited control	Extensive control system
Slow response to emergencies	Fast response to emergencies
Fewer user choices	Vast user choices

Technical benefits

The Smart Grid, by providing intelligent decentralized and distributed controls, will enhance the flexibility of power system. The distributed management of power system will help in isolating faults and creating independent micorgrids. Advanced monitoring will present significant diagnostic information which will help in preventing any major power loss events. With increased automation, the Smart Grid will help in restoring faults in less time keeping the outage time to minimum.

Environmental benefits

One of the major driver of power system modernization is the environmental concerns due to green house gas emissions. The Smart Grid will enable large integration of renewable energy resources for providing green energy and in turn reducing the pollution and green house gas emissions, due to traditional power generation methods.

2.2.7 Technology Areas

The International Energy Agency (IEA) formulated the Smart Grid into eight technology areas (Figure 2.5). These areas and their functions can be described as follows [Mar15]:

Wide Area Monitoring and Control (WAMC): helps power system management with increased (real-time) monitoring, optimizing and controlling it over large geographical areas

ICT integration: is one of the most important enabling technology domain that provides support for real-time monitoring, two-way communication, and spreads intelligence in power system

Renewable and distributed generation: provides the connections to the renewable and other conventional power sources to be connected to power system

Transmission system enhancement: technologies for marking power transmission subsystem more manageable, efficient and intelligent

Distribution Grid Management: enabling technologies for making power distribution subsystem intelligent and better situation aware

Advanced Metering Infrastructure (AMI): an important technology for providing two-way communication between grid and consumer

Electric Vehicle charging infrastructure: necessary technologies to handle the required charging infrastructures and billing facilities for efficient battery charging in electric vehicles

Customer-side system: technologies (or home energy management technologies) are relating to the automated management, monitoring and control of energy requirement in commercial and/or residential buildings.

2.2.8 Worldwide Initiatives

Table 2.2 presents some major Smart Grid activities worldwide that are being carried out by industry alliances, organizations, working committees and independent organizations.

2.2.9 Standardization and Roadmaps

Uslar *et al.* [URB$^+$10] presents a review of standardization efforts worldwide. A summary of their review is presented as Table 2.3 below.

Table 2.2: The Smart Grid initiatives by alliance, technical and staring committees, independent organization worldwide. Source [Bor12].

Initiative	**Description**
European Renewable Energy Strategy	In the perspective of EU Vision 2020, set the renewable energy roles for individual stakeholder
EPRI IntelliGrid^{TM}Methodology	Outcome of Integrated Energy and Communication Systems Architecture (IECSA) study during 2001–2004
EPRI's Smart Grid Demonstration Initiative	The Smart Grid DER integration demonstration with 18 utilities worldwide
Smart Energy Alliance (SEA)	Collaboration between leading companies including HP, Cisco Systems, Intel, Oracle for ICT and energy system integration efforts
GridWise Alliance	An alliance (not for research) with diverse stakeholders for coordinating activities for the development of smart power systems
GridWise Architecture Council	formed by US DOE for working with GridWise Alliance, promoting awareness, developing checklist for stakeholders for interoperability management
IEC Technical Committee 57	international standard development and maintenance for control systems and equipment developed Seamless Integration Architecture (SIA)
IEC Strategic Group 3	collaborating with the Smart Grid projects around the world to provide strategic guidelines and advice, developing framework for interoperability
Low-Carbon Transition Plan	for UK, providing guiding for executing its 5 points plan for climate protection
Smart Grid Information Clearinghouse	a public website for information about the Smart Grid in cooperation with IEEE Power and Energy Society, Virginia Tech, along with some industry partners

Table 2.3: The Smart Grid standardization roadmaps and programs worldwide. Summarized from [URB+10].

Country/Region	**Roadmap/Standard**	**Focus**
Austria	Smart Grid Technology Roadmap	Smart Grid standardization in Austria
Germany	National Smart Grid standardization roadmap	Smart Grid ICT infrastructure
United States	NIST IOP roadmap	Interoperability between Smart Grid and equipment
International	IEC Strategy Group SG 3	Smart Grid standardization
Germany	MoE E-Energy program	ICT in Energy
Germany	BDI initiative	Internet of Energy
International	Microsoft SERA	Smart Grid technology integration
International	CIGRE D2.24	EMS/MMS architecture
EU	Mandate CEN/CENELEC/ETSI M/441	Smart Meters
EU	Mandate CEN/CENELEC/ETSI M/490	Smart Grid deployment
EU		Smart Grid Smart Grid deployment
International	IEEE P2030	Smart Grid interoperability
China	SGCC Plan	Long term plan for Smart Grid development by State Grid Corporation of China
UK	Smart Grid Vision and Routemap	Smart Grid Smart Grid deployment

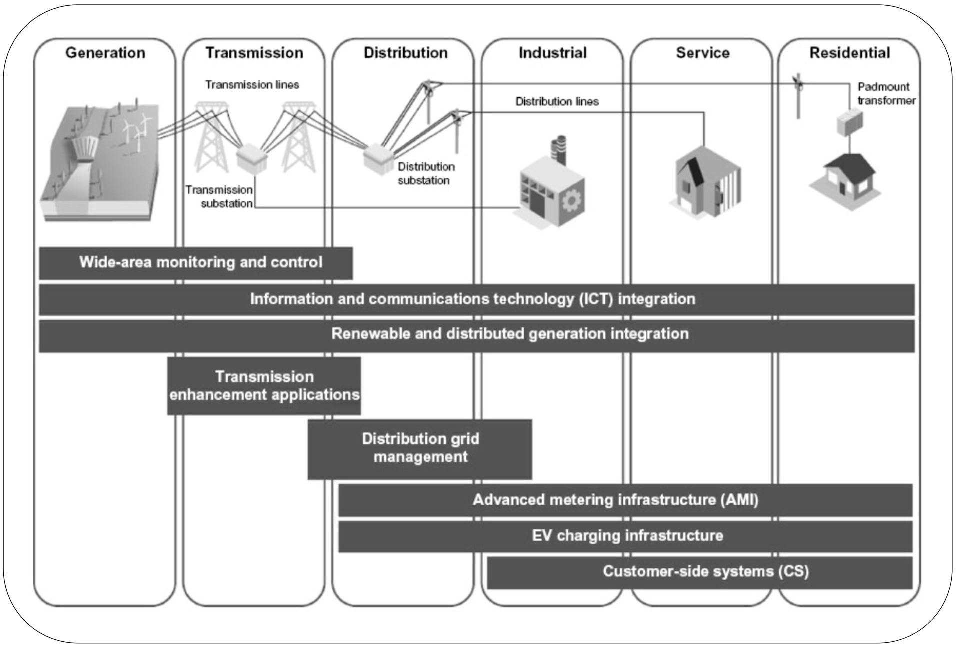


Figure 2.5: IEA identified eight Smart Grid technology areas. Copyrights © OECD/IEA 2011, Technology Roadmap: Smart Grids, IEA Publishing. License: www.iea.org/t&c

2.3 Communication in Smart Grid

From the discussion on the Smart Grid in previous section (Section 2.2), it can be seen that any Smart Grid implementation will have a range of smart devices (embedded computers, smart appliances, smart meters, sensor and actuators etc.) deployed for the monitoring and control of power system. These devices would collect huge amount of heterogeneous data and may receive large number of commands from controllers, to act upon. This important information needs to be transmitted, to the intended recipients in a reliable, timely and secure manner. To support this functionality, a Smart Grid communication infrastructure will be required. The infrastructure will consist of communication technologies, protocols and networking equipment. It will not only provide support for connectivity between the intelligent monitoring and control device but also among the grid-subsystem for distribution and transmission of information. It is envisioned that communication infrastructure will consist of a collection of hierarchically structured interconnected networks. This infrastructure will be communication highway and backbone for the Smart Grid innovative applications [ABC13]. An example of such an end-to-end communication infrastructure is depicted in Figure 2.6.

The remainder of this section presents first, the conceptual and reference models proposed for the implementation of the Smart Grid communication. Next, the communication technologies that can be used in the Smart Grid are discussed along with different applications of the Smart Grid that requires such networks.

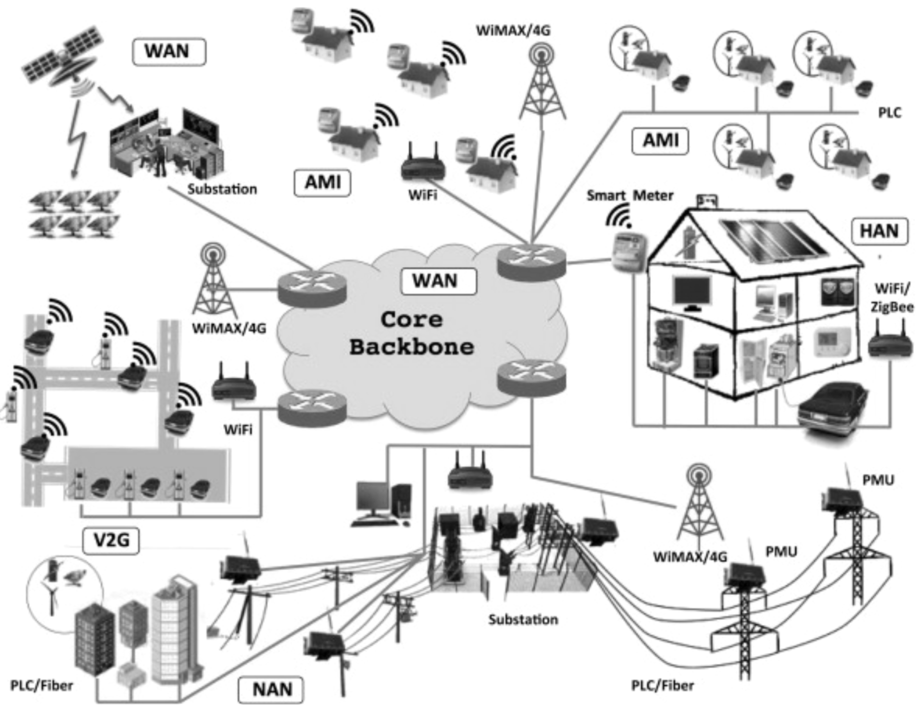


Figure 2.6: An end-to-end Smart Grid communication scenario depicting *Access* tier, *Distribution* tier and *Core* tier. Reprinted from [ABC13] with permission from Elsevier. Copyrights © 2016 Elsevier Ltd.

2.3.1 Reference Models

Due to its importance, communication for the Smart Grid has received much attention. Many reference models and interaction analysis tools have been proposed by national and international research and policy entities. Some of the most import among these are presented here. These model can be used to understand the otherwise complex Smart Grid communication system.

NIST Model

Figure 2.7 depicts the NIST model provided for high-level understanding of the possible interaction between the seven identified domains, in the context of existing applications. It is stated that the model is not a recommendation or a conceptual model for implementation but rather an analysis tool, providing an insight into different types of interactions between domains and applications.

It is further stated that it can be used to identify existing applications that can be ported to the Smart Grid. The model describes different types of networks for fulfilling the information exchange and communication needs for the Smart Grid. Three major network types identified are wide area networks to be used for connection components and sub-system, located a large geographical distance. Field area network provide information exchange and communication link facilities between monitoring and control device including e.g. intelligent electrical devices and transformers etc. Premises area networks provide connectivity between customer and utility, and also can be used to mange "Home Energy Management System" (HEMS) [GWP+14].

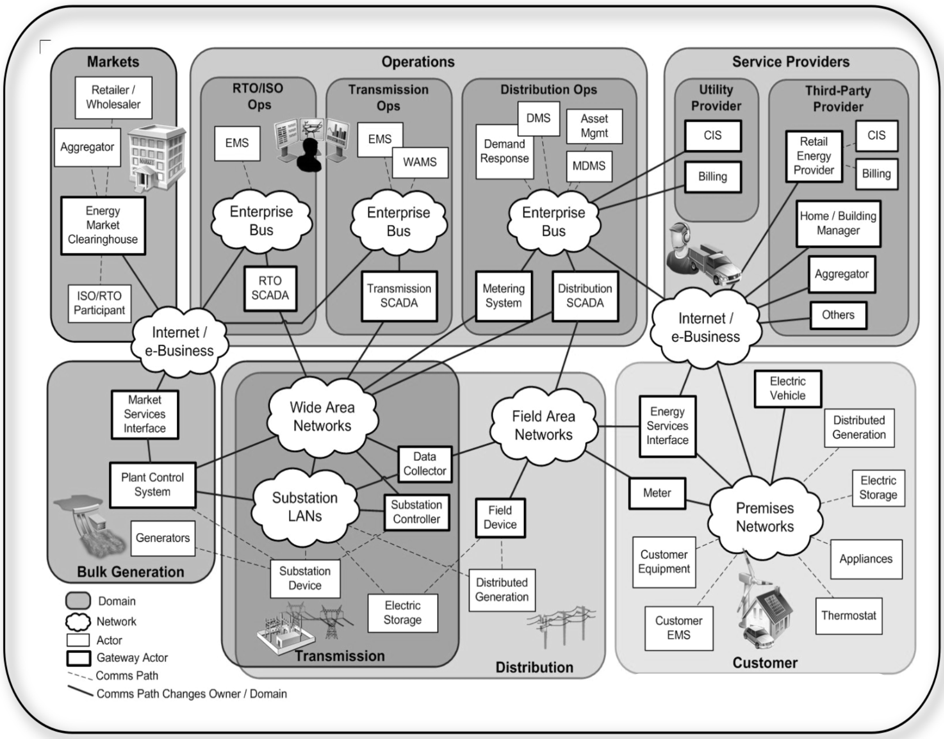


Figure 2.7: NIST Smart Grid Information Networks model in the context of existing power system applications [GWP+14]. Three major networks types are identified for information exchange and communication between the seven domains.

IEC 62357 Reference Architecture

International Electrotechnical Commission (IEC) 62357 [221] TC57 Reference Architecture for Power System Information Exchange (Figure 2.8), is considered to be one of the important and core reference models for the Smart Grid communication standardization. The primary purpose stated, is the identification of boundaries among the existing standards where comparability is needed. The model is divided into layers with each providing different integration applications/services. Layer 1, provides business and application services through middleware, Layer 2 and 3 uses CIM and GID interfaces for data representations while layer 4 represents some distribution and transmission systems and applications, for example, SCADA, EMS, DMS applications etc. [URB+10, TC511].

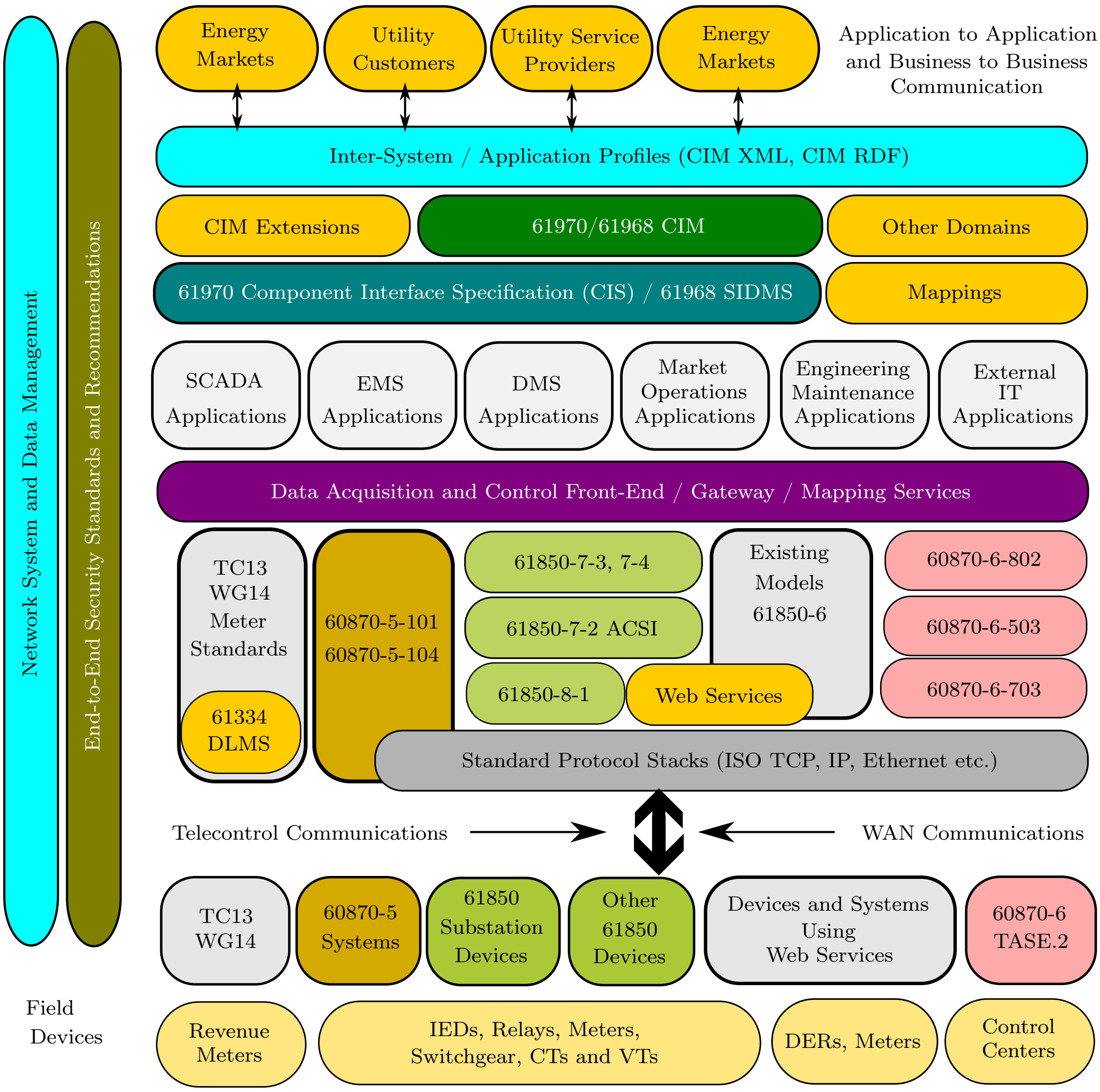


Figure 2.8: IEC 62357: TC57 Reference Architecture for Power System Information Exchange [TC511].

IEEE End-to-End Communication Model

IEEE Std. 2030-2011 present an end-to-end communication reference model in its Smart Grid Interoperability Reference Model (SGIRM) [IEE11]. Figure 2.9, depicts overview of the communication technology interoperability model. It presents a view of relationships between different networks identified for the Smart Grid domains (transmission, generation, distribution and customers). Internet is used to connect networks for all the four domains. Each domain further is divided into many sub networks, while some domains also share same network.

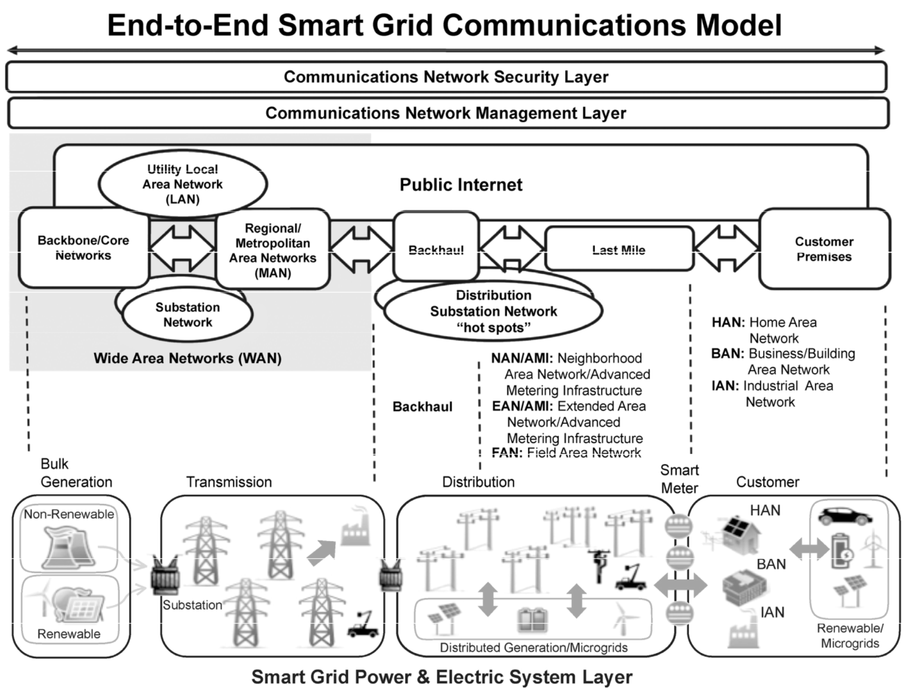


Figure 2.9: IEEE End-to-End Communication Model [IEE11]. Transmission, generation, distribution and customers domains are divided into may networks, connected to each other through public Internet.

2.3.2 Communication Technologies

Different communication technologies can be utilized to provide bidirectional communication between customer and utility, to support monitoring and control of distribution system, and management of distributed energy resources. A partial list of wired and wireless communication technologies utilized in the Smart Grid is presented in Table 2.4.

Table 2.4: A partial list of wired, wireless and Powerline communication technologies for the Smart Grid communication networks [Kab16].

Technology	**Standards**	**Data rate**	**Coverage**	Type
PLC	NB-PLC: ISO/IEC 14908-3,14543-3-5, CEA-600.31, IEC61334-3-1,IEC 61334-5 (FSK); BB-PLC: TIA-1113 (HomePlug 1.0), IEEE 1901, ITU-T G.hn (G.9960/ G.9961); BB-PLC: HomePlug AV/Ext., PHY, HD-PLC	1 *kbps*– 500 *kbps*	≈ 1.5 *km*– 150 *km*	Wired
Ethernet	IEEE 802.3	100 *Mbps*– 10 *Gbps*	100 *m* – 10 *km*	Wired
Fiber optic	IEEE 802.3ah, ITU-T G.983, ITU-T G.984, IEEE 802.3ah	100 *Mbps*– 2.448 *Gbps*	10–60 *km*	Wired
DSL	TU G.991.1, ITU G.992.1, ITU G.992.3, ITU G.992.5	8 *Mbps*– 200 *Mbps* down, 3.5 *Mbps*– 200 *Mbps* up	300 *m* – 1.5 *km*	Wired
WPAN	IEEE 802.15.4, ZigBee, ZigBee Pro, ISA 100.11a	256 *kbps*	100 *m* – 1600 *m*	Wireless
WiFi	IEEE 802.11e, IEEE 802.11n, IEEE 802.11s, IEEE 802.11p (WAVE), IEEE 802.16	54 *Mbps*– 600 *Mbps*	300 *m* – 1 *km*	Wireless
WiMAX	IEEE 802.16, IEEE 802.16j, IEEE 802.16m	100 *Mbps* down / 28 *Mbps* up – 128 *Mbps*	5–100 *km*	Wireless
GSM	2G TDM, IS95; 2.5G HSCSD, GPRS; 3G UMTS (HSPA, HSPA +); 3.5G HSPA, CDMA EVDO; 4G LTE, LTE-Advanced	14.4 *kbps*– 500 *Mbps*	0 – 100 *km*	Wireless
Satellite	LEO, MEO, GEO	2.4 *kbps*– 1 *Mbps*	100 – 6000 *km*	Wireless

2.3.3 Communication Characteristics

The objective of the Smart Grid communication infrastructure is to provide reliable, secure and timely data transmission among its components and sub-systems. The Smart Grid will host heterogeneous monitoring and control data, required to be processed at different levels and applications. Communication infrastructure with variant characteristics would thus be required for at different levels and according to application needs. Knowing these communication characteristics (Figure 2.10), will help in selecting appropriate technology. Table 2.5 presents a guideline for the selection of some of these characteristics for different application data categories (protection, monitoring, control and telephony).

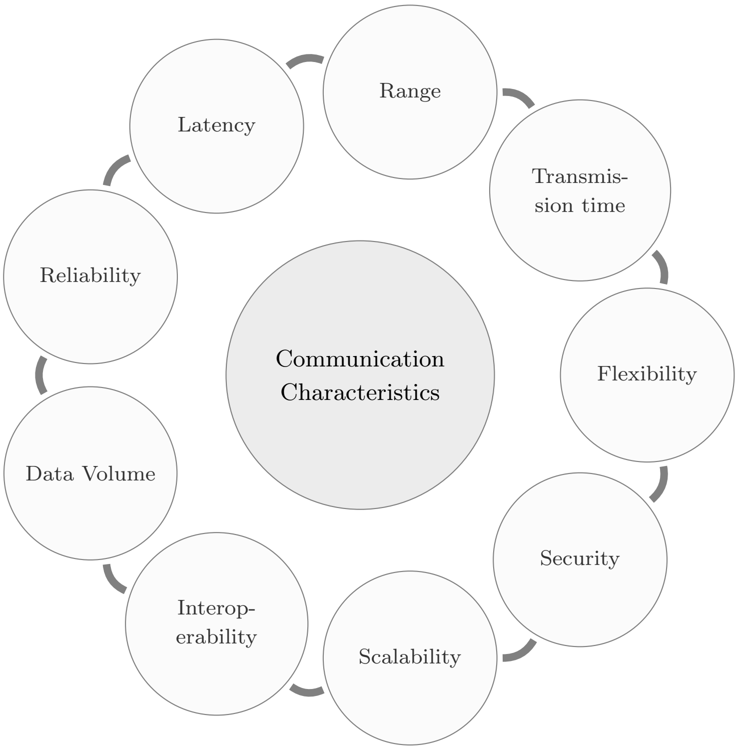


Figure 2.10: Communication characteristics of the Smart Grid [IEE11, ABC13].

Quantitative

Following is a list of some quantitative characteristics as identified in IEEE Std. 2030-2011 [IEE11].

Transmission time: is the time between start of a data transmission from a source entity till the end of complete reception (of same data) at the receiving entity.

Range is physical distance between the two entities wishing to exchange data.

Latency of a communication link is measured in time. The measurement can be taken at multiple points and can include factors such as reception, access and propagation delays. The access delay represents the time it takes to begin transmission once data is ready at the sender. Propagation delay is the time taken by first byte to reach received after it is transmitted. Reception delay is the reverse of access delay. It represents the time taken after the data is received at sender and made available to the lower layers.

Reliability represents the level of importance and can be qualitatively represented as informative, important and critical.

Data Volume is the size (kilo/mega bytes) of data needs to be transmitted.

Qualitative

Further, some qualitative characteristics are listed below as noted in [ABC13].

Interoperability describes the provision of heterogeneous service, protocols and devices to work together seamlessly.

Scalability refers to the ability of the communication network to perform its functions even when many more device join in. One possible solution would be to use distributed communication architectures.

Flexibility is the ability to host both heterogeneous services with different quantitative characteristics and to different communication models.

Security is ability to safeguard confidentiality and integrity of data against any attempt of unauthorized access.

2.3.4 Smart Grid Communication Networks

There are numerous innovative Smart Grid application where communication is an enabling technology. These applications help in implementing the vision of the Smart Grid for a cleaner, cost-effective, reliable, situation aware, self-healing, intelligent and modern power system. Such applications are classified, usually, based on their functions. One such example is the classifications of the Smart Grid application into six functional area by US DoE [242]:

- Advanced Metering Infrastructure
- Demand Response
- Wide Area Situation Awareness
- Distributed Energy Resources and Storage

Table 2.5: The Smart Grid Data categories and communication characteristics [IEE11].

Characteristics	**Application Data Category**			
	Protection	**Monitoring**	**Control**	**Telephony**
Latency	Low (<3ms)	High (<160ms)	Low (<3ms)	High (<160ms)
Time resolution	milliseconds	seconds	seconds	N/A
Availability	high	medium	medium	medium
Reach	2 km	2 km	2 km	2 km
Integrity	high	high	high	medium
Assurance level	high	low	low	low
Data volume	bytes	kilobytes	bytes	kilobytes
Reliability	critical	important	important	important

- Electric Transportation
- Distributed Grid Management
- Microgrids

The summary below presents another classification as per Budka *et al.* [BDT14].

Advanced Meeting Infrastructure (AMI) Network

Advanced Meeting Infrastructure (AMI) is an integrated network of smart meters, data management system and communication networks to support the smart meter deployment. 'Smart Meters' deployment is an import activity in the Smart Grid. A smart meter periodically (time resolution is usually in minutes) send measurement data that is used for many other applications such as demand response, volt-var control etc. In Europe, a potential investment of €51 billion is projected due to smart meter installations by 2020 [FHH09]. A communication network for AMI provides the link, primarily, between a smart meter installed at a consumer's location and the Meter Data Management System (MDMS). This network is used for two-way communication between the smart meter and data management system. Among the few standards available for AMI, ANSI C12.22 and ANSI C12.19 are considered comparatively mature. Different wired and wireless communication technologies, for example, IP, Ethernet, PLC or WiFi etc. can be used for the realization of such network depending on the needs, constrains and requirements.

Distribution Automation Network

A distribution automation network represents the links between deployed IEDs, re-closers, switches, capacitor banks, transformers, phasor measurement units, smart meters etc. and *distribution* *master control*, for the collection of status information. Distribution master control later uses the collected information for the automation of distribution functions. Another part of the distribution automation network is distributed storage. The network requires low latency as the time resolution is usually in some seconds.

Distributed Generation Support Network

The Smart Grid features stand-alone distributed generation units and customer being supplying excess electricity, through the connections with utility network, to grid. For safety and stability, these connection needs to be monitors for any voltage or frequency synchronization issues. Additionally, automated power curtailment remote controls are also needed for connection and disconnections whenever necessary. Low latency, high resolution or real-time networks are usually desired for the implementation of these networks.

Electric Vehicles support Network

Plug-in hybrid electric vehicles use energy from grid to operate in addition to fossil fuel (gasoline, diesel, or fuel cells) stored in them. In the Smart Grid an electrical vehicle can also be utilized as storage. Electrical Vehicle Service Element (EVSE) either embedded into an electrical vehicles or provided as a stand-alone unit, provides the interface between batteries ad grid. A communication network is required between EVSE and the associated utility for authentication, billing, charging and any other management functions.

Home Area Network

One of the envisioned benefits of the Smart Grid for consumers is the ability to control and mange the energy consumption in residential and commercial building by employing the smart devices. Home Energy Management System (HEMS) uses a 'home area network' to communicate with these smart devices and also to manages the local generation (from solar or wind). HEMS can support numerous application for home energy automation, demand response and local generation management. In case of automated demand response, its need to be connected to utility's energy management system over another communication network. Wireless network technologies, for example, ZigBee [237], and power line communication technologies HomePlug [214], can be promising communication technologies for home area network usages depending on the supported device interfaces.

Microgrids Network

The Smart Grid enables the use of Microgrids — collection of some interconnect 'prosumers' within a small geographical area (building, campus etc.), each having some local generation. Consumers can utilize both the energy generated from local sources and through the utility grid. Microgrids generally can work in 'islanding mode', fulfilling the critical local need such as security, elevators and/or lights, in case of any power supply disruption from the utility. Microgrid are emerging with, for example, the increased deployment of distributed energy resources on the rooftops of the large residential buildings.

A microgrid energy management system, requires a communication network for performing energy management within the mircrogird and with the utility. This requires that both power generations and consumption be monitored with appropriate devices installed at each source and load. Also, these devices need to be connected to energy management system through some communication network. Depending on the size and supported device interfaces, different wire or wireless communication technologies (IEEE 802.11x, ZigBee, PLC, Ethernet) can be utilized.

Retail Energy Markets

Traditionally, there has only been single energy market refereed to as wholesale energy market (WEMs) and participated by utilities and bulk power generators. Smart Grid has brought in the well informed customer and large scale distributed energy resources deployment. It is expected that both consumer and *prosumers* will try to get the best economical options for energy prices. This will result in large number of distributed generation owners, desiring to sell generated power for competitive prices. It is also expected that these distributed generations will play an important role for utilities in their energy management needs, by providing the option of buying power whenever needed. Such anticipated developments will create a new energy market — *retail energy market* (REM).

In contrast, with wholesale energy markets where there are only number of participates, retail energy markets will have many thousands of participants. One possible management model is based on a third party entity. According to NIST and CENELEC EU models (Figure 2.4), this entity comes under *service provider* domain. A communication network will be required to connect this entity to its participants and its customers. A low-latency high bandwidth and real-time communication network will be required for the efficient functioning of this retail energy market.

Demand Response

Demand response is not a new concept introduced in the Smart Grid but has been around from the early days of the electrical power system. It refers to keeping the peak power at manageable levels with either reduction in demand (by load shedding) or increase in the energy supply. Both long term (months, years) or short term (minutes, hours etc.) methods can be employed. Also, the customer participation mode can be either voluntarily or enforced. There are many well-know methods for achieving a peak reduction such as dynamic pricing, demand bidding/buyback, retail energy markets, voltage control, direct load control and automated demand response etc.

Communication networks are required in implementing most of these demand response methods. Since, demand response methods vary on time resolution and size of monitoring data, different communication technologies can be used for varied methods.

Wide Area Monitoring and Control

Communication networks are required for, high time resolution, monitoring of interconnection and collection of performance data from power system components distributed over a large geographical area. This process is refereed to as wide area monitoring and control. The collected data, this way, allow important diagnostic information and allow for taking necessary actions to preventing any major blackouts. Phasor measurement units (PMUs) are intelligent electrical device that can measure amplitudes and phase of voltages and currents. Another feature is the extremely high frequency of such measurements, 10-100 measurements per seconds, based on the frequency of power system. PMU measurements are timestamped with GPS synchronized clock. It is expected that many PMUs will be installed in the future. High speed communication network will also be required for connection these PMUs with phaser data concentrators (PDCs). Specification of one such communication network for example is the North American Synchrophasor Initiative network (NASPInet) [MK10].

Dynamic Line Rating

Transmission lines generally have a rated value of maximum current they can carry. This values is calculated considering the worst possible environmental conditions such as ambient temperature, solar radiation, ice accumulation, sag etc. It would be possible for transmission lines to carry more current if for example temperature is low. Knowing this could provide important economical and technical benefits in meeting growing demands. Dynamic line rating (DLR) provides the abilities to monitor environmental conditions through the use of IEDs deployed at or near the transmission towers. It is estimated that DLRs can improve the transmission capacity up to 10–15%. A communication network will be required to gather monitoring data from largely number of such IEDs deployed in transmission system.

2.4 Summary

This chapter has presented a short history and evolution of electrical power system alng with motivating factors towards the modernization of power system. The Smart Grid is the vision of modern power system where information and communication technology layer is integrated with improved power system layer. Major worldwide Smart Grid models, frameworks and roadmap are listed to show the importance of research in this area. Communication as an enabling technology and its applications in the Smart Grid for the modernization of the power system are also discussed.

3 Review of Smart Grid Modeling and Co-simulation

The previous chapter, Chapter 2, has presented the history and transformation of the power system towards the Smart Grid, discussing the major motivations and efforts. It has further, presented the importance and the use of information and communication technology (ICT) in the Smart Grid. This chapter presents an analysis of the literature regarding modeling and co-simulation tools and methods for the Cyber Physical Systems and the Smart Grids. The chapter begins with discussing the importance, motivation and challenges in the research of modeling and simulation of the Cyber Physical Systems and the Smart Grids in Section 3.1. A detailed review of literature regarding modeling paradigms, approaches and languages is then presented in Section 3.2. Literature regarding co-simulation based Smart Grid analysis is presented in different categories, in Section 3.3. Section 3.4, formulates and presents the requirements for a co-simulation based tool-set to fulfill the aim of this dissertation.

3.1 Motivation and Challenges

Research on modeling and simulation of the Cyber Physical Systems (CPS) has received much attention because these systems are being considered as one of the next computing revolution [RLSS10, Lee09]. The CPS are the new class of innovative systems [KM15] having the potential to bring huge social and economic benefits by providing innovative applications in number of areas [SH12], including (but not limited to) transportation [JC12, SP13, ZLC^{+}13], health care [DD15], energy [Kar11], buildings, manufacturing, defense etc. The emergence of the CPS is an evolution from hybrid embedded to networked hybrid-embedded systems [Ach11, FLV14, Ant09, MMP92, Lee08], and has resulted due to innovations and development of two prominent areas; embedded systems and communication networks [FLV14].

In the CPS, the idea mainly is to embed *cyber* into the *physical* world [Lee08, Poo10] to control, monitor and to provide intelligent services. The CPS are dynamical systems with complex interaction of heterogeneous system with both continuous and discrete dynamics. It is argued that the

CPS are not just a combination of `cyber` and `physical` but more. There are complex relationship, interactions and interdependencies with many, yet to be known sources of uncertainties between these tightly coupled system. It is thus not enough to model these systems independently while ignoring their interactions and interdependencies [Lee10]. This fact further indicates that the CPS are very different from the early systems, from where they have evolved. Their shear size, multi-dynamics nature and complexity in addition to their emergent properties like heterogeneity, concurrency, level of abstraction, dynamics of interaction etc. are only some of such requirements which need to be dealt when modeling these systems. The CPS modeling with these demanding requirements in the presence of such constraints "*presents a substantial intellectual challenge*" [Lee10].

Additionally, for the CPS some common model assumptions like non-emergent behavior, dimensionality, time invariance, linearity are no longer applicable. Furthermore, most of the state-of-the-art physical modeling approaches and simulation tools are incapable of capturing the multi-dynamic interactions and interdependencies of *cyber* and *physical* sub-systems, as these approaches and/or tools where not designed to model and simulate such systems. This makes it practical to introduce multi-domain modeling and simulation approaches for the CPS [Lee08, Ach11, BCG12, BCG12, ZHY13, BG13, Bro13, FLV14, PWE14, KM15, MGN+16].

The Smart Grid (Section 2.2) is an innovative application of the CPS, aiming for a power system that is more situation aware, automated, economic, resilient, reliable, and environment friendly. It is termed as the next generation power system [Li14] and has been influenced heavily in Europe by the EU Vision 2020 under EU SmartGrids Framework [Che07, Bie13] and other initiatives [LT14, LRH16]. According to Colak *et al.* [CFS+15], a total of €3.13 billion had been invested till 2014 in Europe alone on the Smart Grid projects. Furthermore, a potential investment of €51 billion, in Europe, is projected due to smart meter installations by 2020 [FHH09].

The Smart Grid utilizes coordinated intelligent monitoring and control to provide better situation awareness and self-healing capabilities. The real-time monitoring and control provides important diagnostic information and dispatching the healing actions. It will also manage significant share of highly unpredictable renewable energy resources that are going to be the part of the future power systems [IXK08, IXKM10, Str12].

The Smart Grid is a complex multi-domain system where power, communication and control sub-systems are mutually dependent and could affect each other (Figure 1.3). It is therefore, a necessary constraint to design the Smart Grid as a CPS [ALL15a]. Although, there are many specialized tools with various abstraction levels for the individual Smart Grid domains, but they are not capable to deal Smart Grid as a whole. Additionally, there is still no tool or method that would be capable of combining these domains seamlessly, incorporating the discrete and continuous dynamics [PWE14].

The rest of this chapter is divided into three further sections. The first two section presents an analysis of literature on modeling and simulation of the Smart Grid (Figure 3.1). In Section 3.2 a survey of the literature for modeling approaches, languages and models suitable for the CPS and the Smart Grid modeling is presented. While, in Section 3.3, a comprehensive analysis of co-simulation approaches is presented. These approaches are categorized according to coupling methods and simulation paradigms. The third section (Section 3.4) presents the requirements for co-simulation based tool-set.

3.2 Modeling Paradigm for Cyber Physical System

Modeling and simulation are valuable tools for explaining a dynamical system and in predicting the behavior under certain conditions and/or changes. The results, obtained from a modeling and simulation studies are useful not only in its improved understanding, management, and evaluation but provides supports in decisions and policy making.

The first step towards modeling is the selection of a modeling paradigm and an abstraction level that could best describe the problem in hand. There is no "one for all" approach, making this choice highly application dependent. This section presets a review of the literature for the modeling approaches, languages and models suitable for the CPS and the Smart Grid design.

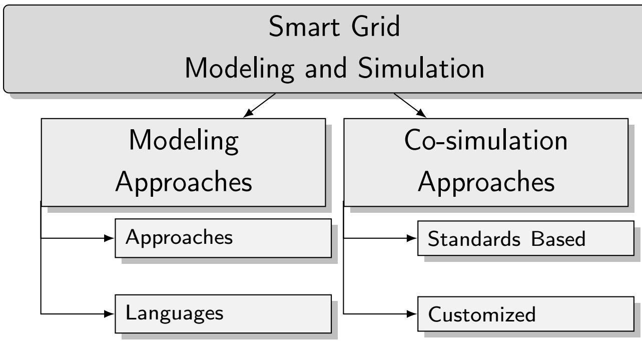


Figure 3.1: Overview of literature analysis presented in this chapter.

3.2.1 Modeling Approaches

A CPS is defined as a system consisting of physical and cyber sub-systems. The physical sub-system represents both man-made and natural systems and interact with the environment in, mostly, continuous time domain. The cyber sub-system represents the computational system involved in processing and controlling activities using algorithms implemented in software and digital systems operating in discrete time domain. As a result, the CPS are highly complex system with distributed, tightly coupled cyber and physical sub-system in discrete and continues dynamics [San15].

A review of literature regarding the modeling approaches for the CPS are presented in this sub-section. It includes work on Model-Based Design, Aspect oriented approaches and some other works.

Model-Based Design (MBD) Paradigm

Model-Based Design is a modeling and design paradigm for complex system with significant differences from the traditional methodology. Advanced functional characteristics can be modeled with discrete and continuous time blocks instead of using complex structures. In Model-based Design, a model plays the central role in every part of the development process. Figure 3.2 presents an overview of Model-based Design paradigm. It has four main elements: desired behavior modeling; design improvements through simulation; automated code generation for implementation; and repeated model verification throughout process. It provides a cost-effective method of complex system design [KKM+13].

The rest of this section presents a review of literature for CPS modeling using the Model-Based Design. The Smart Grid, being a CPS could also be modeled using these approaches.

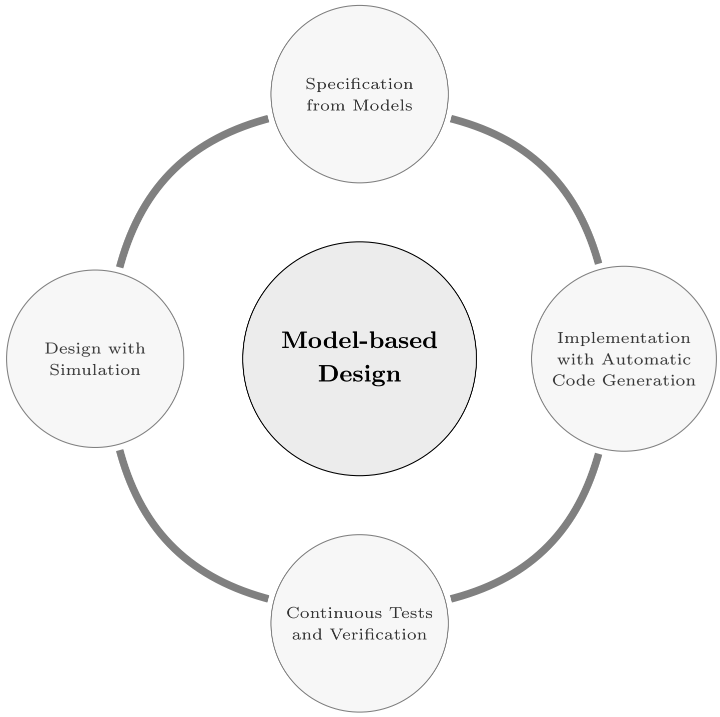


Figure 3.2: Model based Design overview. It has four main interlinked elements: desired behavior modeling; design improvements through simulation; automated code generation for implementation; and repeated model verification throughout process [KKM+13].

The review start with a ten step CPS design methodology proposed by Jensen *et al.* in [JCL11]. In the proposed methodology, the order of execution, of these steps, is not strict and can be tailored according to the needs of the problem in hand. To show the applicability and to demonstrate the modeling process, a toy example is modeled and simulated in Ptolemy [240]. Since, the proposed methodology gives a guideline rather concrete steps (which is a daunting task), it may be difficult to conform to the design requirement without many iterations of individual steps.

Ilic *et al.* [IXK08, IXKM10] proposes a modeling approach to analysis the performance of the Cyber Physical Energy Systems (CPES), considering the effect of sensing and communication. The mathematical model of the proposed dynamic model is focused on cyber and is based on the assumption that required performance of CPES can be achieved by the means of available cyber infrastructure. It represents the heterogeneous cyber and physical component as a module connected through the electrical network according to it constraints. Model developed from such modules can later be used to analyze sensing, communication and control needs. The presented results of modeling a small system, however, shows that they are dependent on the load model that need to be highly detailed.

Another model-based actor oriented CPS design methodology is presented in Chandhoke *et al.* [CHKW11] present a model-based methodology for designing the CPS. A target computing platform needs to be specified first, on this the actors and interconnection can then be built. An actor is assigned a computational model, execution timing actor and clock synchronization. Two actors are connected using wires. Model of a leather cutting machine is evaluated as a case study. Although, the modeling approach can be useful, but it lacks the cyber and the physical interaction modeling.

SICYPHOS (Simulation of Cyber Physical Systems) [MPGD13] is a framework for the model-based design of distributed energy management applications. It is based on SystemC [IEE12] with TLM (transaction level modeling) and AMS (analog and mixed signals) extensions to provide communication and physical modeling capabilities. Another model-based methodology for CPES modeling and simulation is presented in [FA14a]. An example residential microgrid is modeled and simulated with four intermediate steps.

Acker *et al.* [ADVM15] presents an approach to manage the heterogeneity issues in the design of the CPS with MBD. The addressed problem arise when sub-systems are modeled at different levels of abstractions. Combing such heterogeneous models, without care could introduce large errors in the simulation. The proposed semi-automatic methodology consists of six steps designed in a way that the information is gradually added and analyzed for any anomaly in input and output ports and units. However, the modeling approach is highly dependent on annotating each sub-system model with sufficient metadata in accordance with FMU `modelDescription` vocabulary defined in FMI [210].

Aspect-oriented approach

Aspect-oriented approach works on the principle of *separation of concerns*. Multiple simple system-aspect models of a complex system model are developed where each model can concentrate only on one aspect of the system and can be developed independently. Such modeling is useful as it reduces the complexity with focus on one aspect per model resulting in simple and smaller models than other mixed modeling approaches. Additionally, each aspect model can have different level of details and abstraction resulting in added flexibility [Zha11a]. There has been some efforts to model the CPS using Aspect-Oriented Approach. Some work using aspect oriented approaches for modeling of the CPS can be found in [Zha11a, Zha11b, Zha13a, Zha13b, ALL15b].

Other Approaches and Frameworks

Some modeling approaches that have been applied to the CPS are further presented in this section. These modeling efforts are presented in a separate section since they can not be classified in the above categories.

Talcott *et al.* [Tal08] describes event-based semantics for modeling of CPS. Different notations of events along with challenges in developing an event-based approach are discussed. It is argued that the proposed semantics are a natural way of representing components of CPS. Two computational agents models, interactive and autonomous, are proposed while arguing that interactive agents model is more suitable for CPS.

Development of a theoretical framework to provide *cyber* and *physical* co-design is discussed by Zhang *et al.* [ZSWM08]. The problem of controller performance and robustness is addressed by presents a scheduling algorithm by employing the feedback laws. The objectives are stated as being able to provide for both predictable performance and power dispatch. These objectives are shown to have achieved in the presented example of a multiple inverted pendulum system being controlled by a single processor.

To conduct a formal spatial and temporal analysis of CPS, a framework is proposed by Tan *et al.* in [TVG09] based on properties of events. An event is laid down with the attributes of spatial and temporal conditions. To capture the complex *cyber* and *physical* relationships, a layer event model with composite events is prepared. A composite event is captured by combining different types of event conditions using logical operators.

A framework consisting of a stochastic model for multi-agent CPS and a formal logic, SafAL (safety analysis logic), for representing safety properties is presented by Bujorianu *et al.* in [BBB09]. An agent is modeled as a stochastic hybrid system and is considered to have continuous physical mobility; while in SafAL the probabilities and epistemic operators are combined. Using formal logic, reachability properties of the agent and commands for the user can be specified. The presented framework is user centric and can model both human users and automated control.

Dabholkar in [DG09] presents a feature oriented software development (FOSD) principle based approach, utilizing Origami matrices and generative programming, for systematically customizing a middleware for designing CPS. The approach is intended to be capable of adding, removing and optimizing application specific features. The proposed specialization approach emphasis on code-reuse that is more feasible than designing a middle-ware for individual CPS application. This saves cost and time in designing, maintaining and testing such systems.

An architectural level modeling and analysis tool for CPS is presented by Rajhans *et al.* in [RCS+09]. The tool contains a set of architectural style, behavioral annotations and verification modules. The architectural style compensate the lack of current software architecture styles (components and connectors) in representing CPS. The architectural style are used to describe the structural information while behavioral annotations are used to attach useful information. This information is functional while conducting formal system analysis. The architectural styles, verification plug-ins and behavioral annotations are implemented using Acme ADL [GMW00]. The tool is helpful in providing a unified environment for modeling and verification of both *cyber* and *physical* components of a CPS.

Hilbertean formal method is an approach for CPS design presented by Bujorianu *et al.* in [BB09]. It is aimed at providing formal semantics that are capable enough to describe both the cyber and the physical aspects. In contrast to classical solutions it uses the weak solution of complex differential equations on the arguments that there always is a weak solution to every complex equation. The proposed semantics for physical components are further combined with mathematical models of monitoring and control.

Lee [Lee10] describes and compares two approaches, CtP (*cyberizing* the physical) and PtC (*physicalizing* the cyber), for CPS modeling. Cyberizing the physical refers to wrapping the *physical* sub-system with a software abstraction layer. While, physicalizing the cyber refers to the contrast view of wrapping the *cyber* sub-system into an abstraction layer suitable for physical sub-system modeling. The challenges in prior case is porting the notation of time in physical-subsystem into cyber-subsystem and problem in representation of such time. While, in the latter case the challenge is incorporating the missing temporal semantics into discrete cyber sub-systems. A *superdense* model of time is proposed to overcome some of these challenges. Although, the modeling approach is useful and provide some theoretical foundations but support of such modeling is still not possible with state-of-the-art modeling approaches.

Yue *et al.* [YWR$^+$10] proposes a modeling technique called ADE (Adaptive Discrete Event). An event represents a change and contains the location and time of the change. Alteration of environment for which the CPS is designed could cause abnormal events to be generated. Such events could cause control problems leading to an inconsistent system. To address the inconsistency and unexpected events, DEC (discrete event calculus) with abstraction is utilized. An intruder system example is used to demonstrate the usefulness of the technique.

An open and loosely coupled architecture based on Service Oriented Architecture (SOA) is presented by Zhang *et al.* in [ZZ15] where AADL is used as modeling tool. A CPS is divided into three layers, environment, control and service layer. Environment layer deals with distribution function optimization, control layer handles the monitoring components while service layer provides method of reusable services.

3.2.2 Modeling Languages

Like the modeling approaches, there are many languages that may be useful for CPS modeling. This subsection describes some modeling languages that have been used for modeling the CPS in general and the Smart Grid in particular.

Modelica

Modelica [224] is a modern multi-domain object-oriented modeling language for hybrid dynamical systems. A group of researchers, representing both the industry and the academia, was formed in September 1996 with the mandate for developing a unified object oriented modeling technology. After one year, the first version of Modelica language was released [EMO99, Fri11].

In Modelica, system modeling is done through equations. For this purpose, different formalisms including bond graphs, finite state automata, Petri nets, differential algebraic equations (DAE) and ordinary differential equations (ODE) etc., in addition to the high level (composition diagrams) and detailed modeling (equations) is supported. Furthermore, acasual modeling is support to provide re-usability [EMO99].

Many researchers evaluated the suitability of Modelica for different CPS. Junjie *et al.* [JJJ+12], after reviewing the modeling challenges in CPS, evaluates the suitability of Modelica for modeling such systems. It is concluded that Modelica is capable of overcoming many such challenges. Elsheikh *et al.* [EWP12], discusses the capabilities and advantages of using Modelica for modeling CPES.

Different libraries have also been developed to provide any missing components or to support a specific application. Liping *et al.* [LXX+12] presents a Modelical library to support CAN real-time serial communication protocol based CPS modeling. Elsheikh *et al.* in [EAWP13] commending the Modelica success, discusses the ways Modelica components can be *embedded* into simulation tool of user choice.

Automotive Engineers Architecture Analysis & Design Language

The International Society for Automotive Engineers Architecture Analysis and Design Language (SAE AADL) is a hierarchical, component based modeling language, designed for model-based analysis of system-of-systems architectures. It is based on US Army and DASRP MetaH language and is focused on designing safety-critical system [FG12]. The language was approved as SAE Standard AS5506 in 2004 and subsequently revised in 2012 as AS5506B [233]. The language describes a system as composed of different software components on top of an execution platform. The functional properties of individual component like input and outputs, timings can be specified in addition to interaction and execution behaviors [FG12].

Many researches included AADL in the CPS and the Smart Grid design process. Guan *et al.* in [GY13] divides the CPS modeling into static structures (mainly physical components) and dynamic behavior architectural layers. The paper then argues that since the dynamic behavior layer is influenced by the static structure layer, ignoring the static structure modeling introduces flaws in the overall CPS model. Proposed extended AADL is used to model physical components along with the HYSDEL [TB04], [215] for dynamic behavior modeling.

Raghav *et al.* [RGR+09] and Passarini *et al.* [PFFB15] propose approaches aiming at transforming the functional models into architectural models. They address the problem of functional models, used for simulations, not being easily reusable. Both approaches transform MATLAB/Simulink models in AADL architectural models. In case of [RGR+09], this transformation uses System Description and Analysis Language as intermediate step, while for approach in [PFFB15], MATLAB/Simulink model elements are directly translated into AADL elements. Another set of mapping rules that transform Modelica [224] models into AADL are presented in [LZ15]. Similarly, a method to AADL transformation from CA (Cellular Automata) is presented in [Zha13c].

Others

In addition to the modeling languages presented above, some other have also been employed for the modeling of the CPS. A brief review of some languages is presented below.

Hybrid dynamical system modeling and verification languages like CHARON [AGH+00], CheckMate [SRKC00], HyTech [HH94] etc. may be used to model the CPS. However, there are less evidence for such an effort, due to shortcomings, for example, identified in [HKK13] for CHARON. To overcome these shortcomings, an extension of ExCHARON is proposed. It is said to have improved the readability and expressiveness in modeling the CPS. These improvements are due to enhancements like graphical representation for modes and variables, changes the communication methodology and addition urgent transitions etc.

3.3 Co-simulation based Smart Grid Analysis

The previous section presented a comprehensive review of literature for the modeling paradigms, approaches and languages suitable for the CPS and the Smart Grid modeling. This section presents an analysis of literature for co-simulation of the Smart Grid.

3.3.1 Co-simulation Overview

In Tuncer I. Ören's words, a simulation "*is experimentation with models*" [Ö81]. Before describing co-simulation, it would be enlightening to presents some views from the literature about simulation and it challenges for multi-dynamical and complex system like the CPS and the Smart Grid.

The Smart Grid has brought with it new technologies, novel interconnection and interactions, market, *procumers* and a large dependency on information and communication technologies [PWSE13]. Designing such systems in a satisfactorily way is still an unsolved problem due to the requirements like co-ordination between heterogeneous sub-systems and adaption to time-varying *cyber* and *physical* contexts [Tri15]. These challenge has been motivating research resulting in many modeling and simulation approaches being proposed.

For the simulation of coupled systems (like CPS), Felippa *et al.* [FG88, FPF01] describes the following three approaches:

The *elimination* approach Decompose the system by model reduction or integral transformations and then simulate the decomposed model simultaneously using a time stepped scheme.

The *monolithic* approach Representing the whole coupled system as one big monolithic model and simulating in a time synchronized scheme.

The *partitioned* or *decomposition* approach Treating each sub-system as independent module simulated with individual time steps. Synchronization, substitution and prediction techniques can be used to view the behaviors and effects of sub-systems interacting each other.

While, the elimination approach is limited in its applicability to linearly decomposable problems and could lead to numerical difficulties, the other two approach are widely applicable [FG88, FPF01]. The monolithic approach requires a system specification language/method that could support sub-systems at different level of abstraction. But its long been said [HLMV$^+$99], and is still true, that such a universal language is far from reality. Kuebler *et al.* [KS00] supports the decomposition approach as the preferred way of modeling and simulation for complex engineering systems, due to it many advantages.

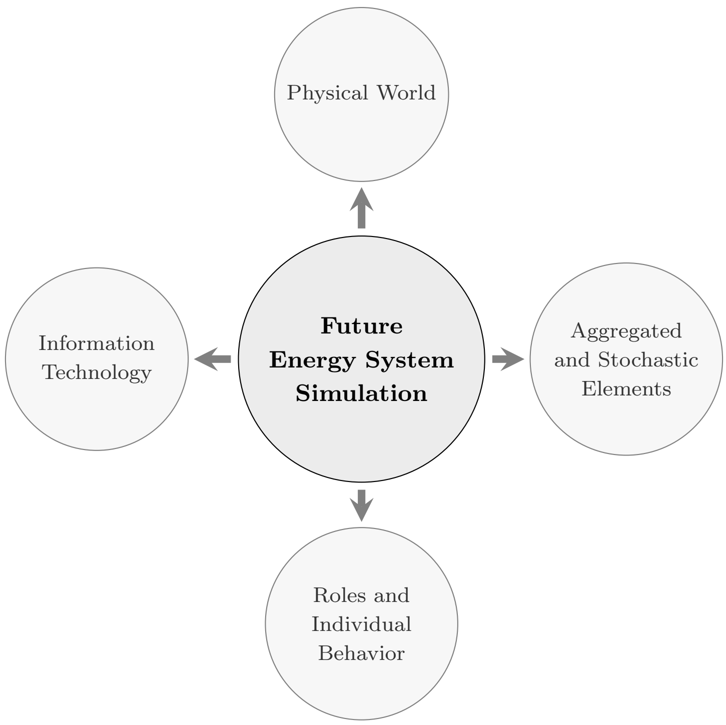


Figure 3.3: Future energy system simulation is required to include the four domains – physical world, information technology, roles and behaviors, and aggregate and stochastic elements [PWE14].

While discussing the requirements for future energy system simulations, Palensky *et al.* [PWE14] identifies four domains – physical world, information technology, roles and behaviors, and aggregate and stochastic elements – as depicted in Figure 3.3. They further argue that there are two possible simulation approaches for such system; monolithic and *co-simulation* [PWE14].

Developing a new integrated simulator (monolithic approach) that could simulate all aspects of a Smart Grid– power system, communication, and control – is not a feasible option in terms of cost, time and complexity. Providing the level of abstraction, details in modeling and sophistication as is usually available in a domain specific tools is not easily achievable. The software could take years and thousands of men hours to attain a reasonable representations and simulation. Furthermore, learning a new software and/or language by every domain expert involved, just for the sake of integration may not be a viable option [LFS+14].

The other alternative is to use co-simulation (Figure 3.4) – combining individual domain-specific simulators in a loosely coupled fashion and simulate them in a coordinated way where participating simulators may not be working with the same modeling paradigm – providing maximum flexibility with minimum implementation efforts. With co-simulation, different Smart Grid domain experts can use their specialized domain specific tools for modeling and can avoid learning a new tool just for integrating models. This saves both the time and cost. Furthermore, using co-simulation further results in re-use of existing models, libraries and expertise. Co-simulation is considered to be one of the important methods for solving multi-domain and multi-dynamical problems [LFS+14, PWSE14].

The co-simulation can be achieved in two different approaches. In the first approach, not popular and provide limited modeling and simulation capabilities, where one of the individual simulation tool is extended to provide the support for other two. While, in second, a more flexible approach, independent simulator for individual domains are combined through co-simulation interfaces to provide a simulation of the Smart Grid. However, providing such co-simulation is not a trivial task as it may requires to co-ordination between heterogeneous sub-systems and adaption to time-varying *cyber* and *physical* contexts [LFS+14, Tri15].

3.3.2 Standards based Simulator Coupling

There exists some co-simulation standards with an objective of providing a standardized API and common simulation interface that would further provide interoperability and reuse. Among the prominent of such standards are HLA (High Level Architecture) and FMI (Functional Mockup Interface). This section review the literature using these standards for simulator coupling in a co-simulation for the Smart Grid analysis.

High Level Architecture (HLA)

HLA (High Level Architecture) [IEE10] is a general purpose, meta-standard for distributed simulation interoperability, developed by the US Department of Defense (DoD) in 1995 [DSB+99]. The

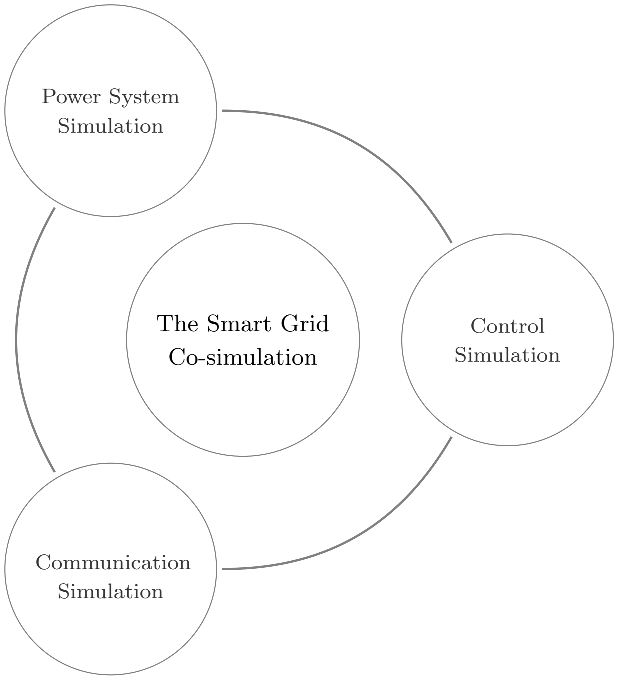


Figure 3.4: An overview of multi-dynamics Smart Grid co-simulation approach. Individual, existing domain-specific simulators are combined in a loosely coupled fashion. The participating simulators are not required to be following the same modeling paradigm.

standard provides structural basis for developing inter-operable simulation components (*federates*) that can be combined to create a simulation (*federation*). According to HLA definition, the time at federation (global) level is maintained by RTI but each federate can maintain its local virtual time. Federates can use the RTI services to request a local time advance. Figure 3.5 depicts a functional view of an HLA federation.

The HLA is focused on the principle of re-usability and its Federation Object Model (FMO) provides the option for re-using the simulation components (federates). In the implementation perspective, Runtime Infrastructure (RTI) is at the core of HLA implementation. It works similar to a distributed operating system for the federation and provides a set of services like communication, data exchange, synchronization along with federate regulations [DFW97, DM98, KWD99, Awa14].

The HLA is a popular standards and have been extensively used for many areas (military application, manufacturing, robotics etc.) including the CPS and the Smart Grids. Bellow is a review of the work that uses HLA for simulator coupling in the Smart Grid co-simulations.

To provide an ease in using HLA with existing simulators and reducing the complexities in communication among heterogeneous federates, a general purpose simulation coordination middleware, DCB (Distributed Co-simulation Backbone) is presented in [MW02]. It proposed an interface, ambassador, for Both DBC and federate connection. An *ambassador* defines the gateways for data format translation and communication. BDC provides both synchronous and asynchronous

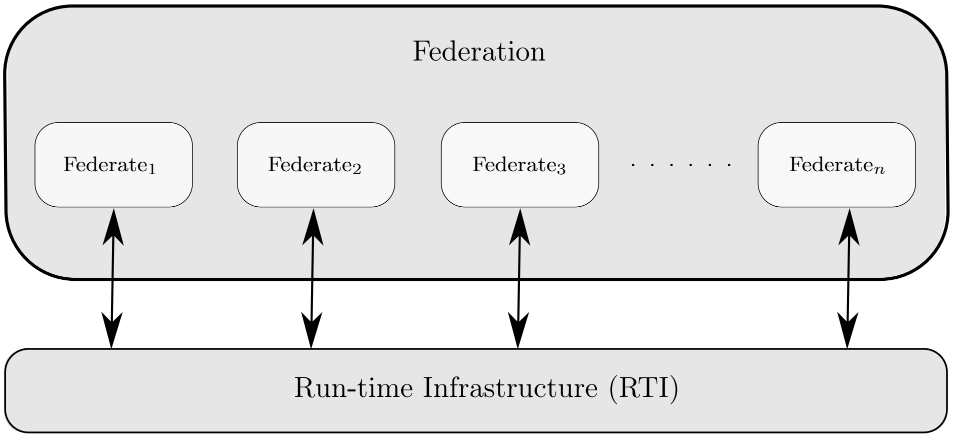


Figure 3.5: Functional view of the High Level Architecture. Inter-operable simulation components, called federates, can be combined through RTI to compose a distributed simulation, called federation [TTN+16].

time synchronizations but for using an asynchronous mode, the *federate* must support a rollback to its previous stable state as it may need to handle the events with timestamps in the past.

Among the first attempts to use HLA for the Smart Grid co-simulation is EPOCHS (Electric POwer and Communication Synchronizing Simulator) [HWG+06]. It employ a multi-agents system (MAS) approaches. The HLA federation uses PSCAD/EMTDC or PSLF federates for power system and ns-2 federate for communication simulation. A modified IEEE 50 generators test case is used to assess a protection system whereas IEDs are modeled with agents. For communication modeling, only TCP and UDP applications are considered. Also, RTI time synchronization is fixed that could result in either a loss of efficiency or accuracy.

Another multi-agents, HLA based Smart Grid analysis co-simulation environment is proposed by Shum *et al.* in [SLM+14]. HLA federation consists of PSCAD (power system simulator), OPNET Modeler (communication simulator) and JADE. Due to the use of commercial OPNET Modeler, it is capable of details communication modeling. No results are reported on any Smart Grid application using the proposed environment.

A power system management and control algorithms design environment based on HLA is presented by Molitor *et al.* in [MGZM14]. The simulation execution time is further enhanced by enabling it to run on parallel computing facilities. A commercial RTI (TLK TISC) is used which uses TCP/IP sockets for communication. Proposed environment employs a sophisticated simulation layering and execution model. Each simulation is divided into three layers (network, control and entity). At network layer, power system is simulated using commercial Neplan simulator, MATLAB/Simulink [223] along with IBM ILOG Optimization Studio are used for energy management control algorithms simulation while entity models developed with SimulationX are simulated with PEF simulator. Although, presented comparisons of serial and parallel executions run times shows significantly reduced in the latter approach, the results can not be generalized due to high dependent on the simulated scenario.

For the assessment of wireless networks performance, an HLA based co-simulation environment using OPNET and MATLAB is presented by Zhang *et al.* in [ZYL12]. Although no Smart Grid application is demonstrated using it, but it is possible to extended the environment to include some power system simulator.

A recent and comprehensive Smart Grid co-simulation environment called INSPIRE (Integrated co-simulation of power and ICT systems for real-time evaluation) is presented by Georg *et al.* in [GMRW14] and [GMD+13]. It is based on HLA with DIgSILENT PowerFactory for dynamic power system simulation, OPNET Modeler for communication simulation with a synchronized and connected through Pitch pRTI (a commercial RTI). INSPIRE is focused on wide-area monitoring, protection and control (WAMPAC) applications. These WAMPAC applications are reported to be modeled using MATLAB, JAVA, C++ and GNU R.

Albagli *et al.* [AFR16] have very recently presented another HLA based co-simulation framework for the assessment of the Smart Grid applications. It integrated OMNeT++, JADE and MATLAB/Simulink using an open source RTI implementation Portico [228].

The HLA has some challenges that need to be considered while using it. First is the high licensing cost followed by difficulties in making existing simulators compliant with the HLA specifications. Although, latter can be addressed by developing a wrapper for the particular simulator but this might limit the underlying simulator's functionality and would be quite difficult when simulator source code is not available (proprietary commercial software). Yet another challenge is the way federates communicate and forwarding every updates to subscriber putting additional overheads [HWG+06, MGN+16]. It should also be noted that HLA only provides the solutions to technical interoperability (RTI, coordination and management of time synchronizations, conformance etc.) issues while rest (conceptual and functional) are the responsibilities of designer [DSB+99]. Since these challenges are inherent to HLA, they apply to most of the work discussed above.

Functional Mockup Interface (FMI)

FMI (Functional Mockup Interface) [210] is a tool independent standard for dynamic simulation model exchange and co-simulation [BOA+11]. The FMI Version 1.0 was published in 2010 by Daimler AG [203], while the current version 2.0 was released in July 2014 [BOÅ+12]. The focus of standard is to provide a tool independent model exchange and tool coupling interface for solving the problem of simulation models sharing between the components developers and integrators (OEM) [ERCS+11].

The FMI Version 2.0 supports both model-exchange and co-simulation. In FMI for Model Exchange a `C` source code or a compiled DLL generated from one modeling and simulation environment could be subsequently utilized by another. While, FMI for Co-simulation provides a standard interface for the coupling of different simulation tools and self-contained simulation models. A *Master algorithm* is used for the synchronization and data exchange services. Theses models (in case of FMI for Model Exchange) or co-simulation slaves (in case of FMI for Co-simulation) are distributed in a zip file called a Functional Mockup Unit (FMU). The FMU is considered to be self-contained with an XML configuration file, model code and solvers, along with any other relevant data [BOA+11, Fri15]. A functional overview of the FMI 2.0 is depicted in Figure 3.6.

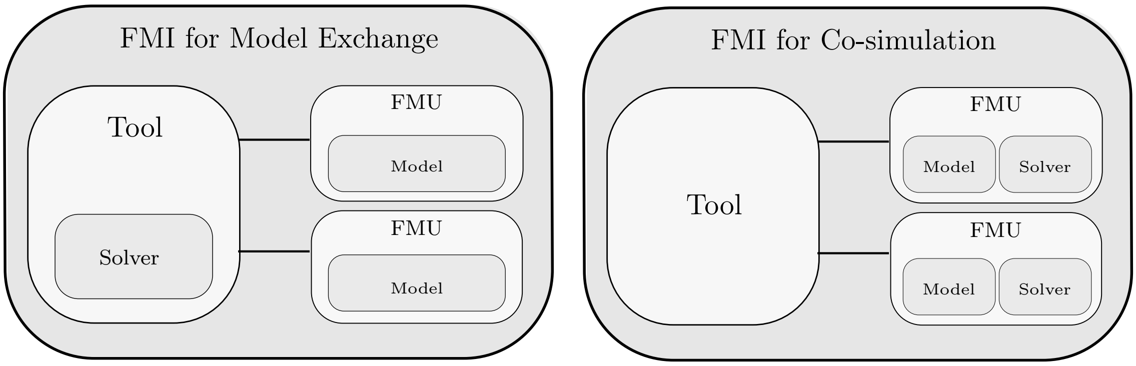


Figure 3.6: A functional overview of FMI 2.0 [225]

The FMI for Co-simulation has been used in many Smart Grid co-simulation environments. A recent FMI based environment VirGIL (Virtual Grid Integration Laboratory) is proposed in [CBM+16]. It is implemented on CyPhySim distribution of Ptolemy II framework [240]. FMU are developed for DIgSILENT PowerFactory and OMNeT++. These tools are then integrated into Ptolemy using FMI with a focus on measuring the effects of different demand-response strategies on the underlying power system.

DACCOSIM [GVD+15] is a distributed generalized co-simulation environment based on the FMI. It provides a GUI interface for designing the co-simulation. It also supports running the simulation in parallel to decrease the execution time. Each FMU is connected through a FMUWrapper. This wrapper provides the data exchange and co-ordination facilities. The simulation can run either with a constant or variable time-step manner. After every time-step, the FMUWrapper exchange data as per configured connections. Another such environment is presented in [SBC14].

Certain challenges make the FMI adaption difficult. The FMI specifications only provides a low-level C API interface. For any simulation and modeling tools, supporting such interface obligate many additional requirements. Fulfilling such requirement is expensive, time consuming and in some cases (proprietary closed source) not possible. Widl *et al.* in [WME+13], provide an open-source object-oriented library (FMI++) while other such libraries include FMU SDK, FMI Library, PyFMI, JFMI etc. Although these libraries provide some aid, this does not reduce the interface obligations. Also, the FMI standard does not provide any specification for a master algorithm. Although, there are many proposed implementations in the literature (see for example [BCWS11, APE+13, SBC14, GVD+15]) but these implementations often are highly application dependent.

3.3.3 Customized coupling Solutions and Approaches

Although, the standardized simulation frameworks like HLA (Section 3.3.2) and FMI (Section 3.3.2) provide better interoperability and scalability, but sometimes a more tailored solution is required. Although, such solutions can provides much more freedom but have to handle many more details. This subsection presents an analysis from literature for many such customized approach for real-time, synchronize and multi-agents system co-simulation works addressed towards the Smart Grid analysis.

Multi-agents System (MAS) Approaches

Although, multi-agents system are around from a long time but still there is no unified definition of an agent. According to Wooldridge [Woo99]:

> "An *agent* is a computer system that is *situated* in some *environment*, and that is capable of *autonomous action* in this environment in order to meet its design objectives."

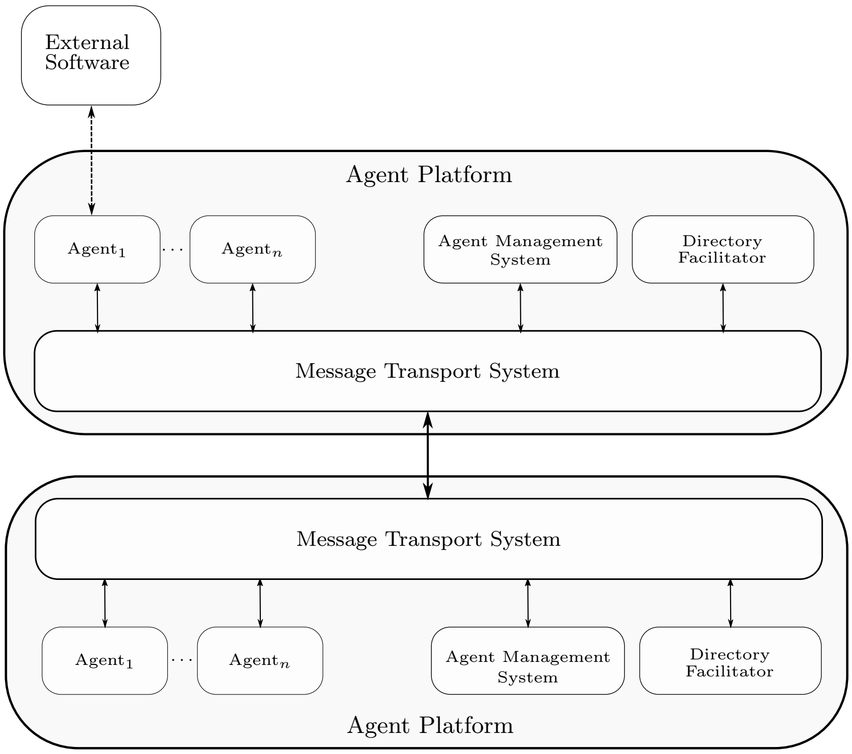


Figure 3.7: FIPA Agent Management Reference Model. The model shows six logical components; agent, agent management system, directory facilitator, message transport system, agent platform and software [208].

According to this definition an entity will only be called an agent when it can be separable from the environment and could perform its actions autonomically.

In recent years Foundation for Intelligent Physical Agents (FIPA) standards and specifications have become widely accepted architecture for inter-operable MAS development [MDC$^+$07a]. Figure 3.7 below depicts the FIPA Agent Management Reference Model that provides a logical reference model for creating, registering, locating, communicating, migrating and retirement of agents [208].

Agents inherently have some properties like distributiveness, autonomy, reactiveness and proactiveness, socialability etc. These emergent properties makes MAS suitable for designing flexible, fault tolerant and extensible system. These facts have made them attractive for many power system applications as well [MDC$^+$07a]. Below are some selected co-simulation frameworks where MAS approach has been used for analyzing the Smart Grid applications.

For modeling and simulating multi-agents system, along with the power system, for a Smart Grid analysis, another framework is presented in [RNBS12]. PowerWorld Simulator, MATLAB and JADE are the tools used for power system, control algorithm and agents respectively. PowerWorld's `SimAuto` add-on is used to provide a COM interface for MATLAB while a TCP socket interface is used for MATLAB and JADE communication. A feeder reconfiguration and large scale demand response are two examples simulated with presented framework. However, as JADE's `InterfaceAgent` merely provides a one-way communication channel, MALTAB can only receive and can not send anything back, making it less attractive for some control applications. No communication simulator is used for accessing the communication dependencies and effects.

Razaq *et al.* [RPTY15] presents a co-simulation scheme based on communication simulator ns-2 and GLD power system simulator. Both simulators are coupled into a single OS process, where execution is started by ns-2 agent module. This agent module (named AgentGL) works more like a simulation coordinator. However, combining two separate simulators into a single application would introduce further complexity and may violate some standards like modularity. Another problem with this approach is that it can not be used with closed source simulators.

Real-time and HIL Approaches

Hardware-in-Loop (HIL) simulation is a type of simulation where physical hardware is integrated as part of the simulation environment. Generally, these types of simulations are considered very powerful due to their abilities in providing testing of the real hardware. It lies between the two extreme simulation approaches – the *software only* and the *hardware only* approach [JLB11]. As depicted in Figure 3.8, the trade off associates with these two extremes are that in the case of software only, generally, there is a high simulation runtime while the hardware only approach is associated with high cost of implementation. The HIL simulations are usually not well suited for large scale simulations projects. Additionally, there may be extra configurations or special interface requirements for connecting hardware and/or simulating different scenarios.

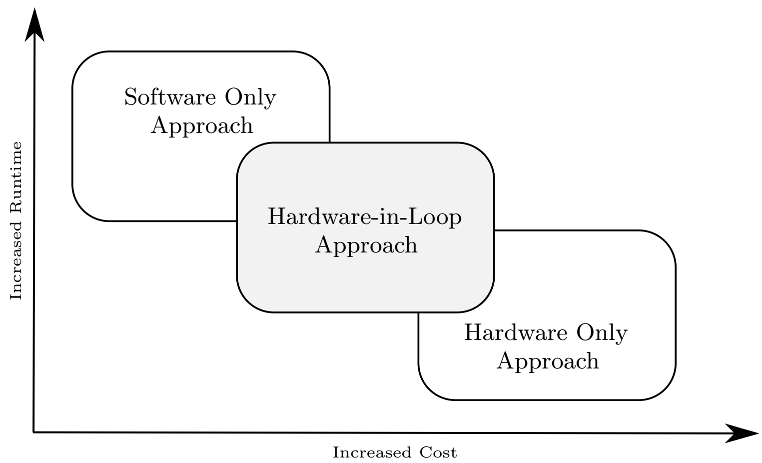


Figure 3.8: Hardware-in-Loop simulation lies between the Software and Hardware only approaches [ASS13].

HIL approach has been extensively studies for the co-simulation of the Smart Grid applications. A review of some of the selected co-simulation work involving hardware-in-the-loop approach has been analyzed and presented below.

A hardware-in-the-loop Smart Grid physical and control simulation environment is proposed in [ASS13]. The tools are coupled using TCP/IP sockets interfaces to each other with IEC 61499 information model. Since, it runs in real-time, no simulation synchronization is required. MATLAB/Simulink and DIgSILENT PowerFactory are used for DERs and power system simulation respectively, while 4DIAC and ScadaBR are used to simulate the control and SCADA environment. Voltage control of a residential low voltage network with OLTC (On Load Tap Changer) is simulated to show the effectiveness of proposed environment. However, it do not provide any communication simulation, analysis like measuring the effects of communication on control strategy and on the underlying power system can not be done.

Another platform with real-time simulation for wide-area monitoring and control (WAMC) testing in a Smart Grid is presented in [BCZ$^+$13]. A WAMC is built on devices like phaser measurement units (PMU) for providing GPS based time synchronized measurements. OPAL-RT, a commercial real-time simulator is used for power system simulation along with MATLAB/Simulink. OPNET Modeler is used for communication modeling of the WAMC network. The platform do not provide the capabilities of control system simulation and hence limits it scope.

Yang *et al.* [YZYV13] presents a hardware-in-the-loop (HIL) event-driven co-simulation environment for distributed control application analysis in the Smart Grid. The controllers are modeled with IEC 61499 Functional Blocks and later coupled with plant models in MATLAB/Simulink through the TCP/UDP sockets. However, the simulation of communication infrastructure between the controller and plants are not addressed.

SGsim [ABG14, ABG16] is a co-simulation framework that support real-time simulations of different Smart Grid applications. OMNeT++ is used for communication system modeling while OpenDSS electrical power distribution system simulator is used for power system. Nlopt and lpSolver open source optimization tools are also integrated into the environment. Communication interface between the simulators is not discussed. The environment do have any control system simulation support, making it not suitable for scenarios where control strategies are needed to be evaluated.

PSMIX-P (Power System Management and Information eXchange Platform) is another real-time HIL co-simulation testbed presented in [BNF+14]. It is aimed at MAS based power flow consensus problems in the Smart Grid applications. Commercial real-time simulation suite, eMEGAsim consisting of OPAL-RT SimPowerSystem and RT-LAB along with its hardware is used for power system simulation. OPNET Modeler STIL (system-in-the-loop) module is used for providing capabilities for connection real network components to virtual, within the communication model. Protection system modeling is carried out with commercial MACH3 high performance control and protection system. Different examples with MAS based controller schemes are evaluated for bit error rates when a disturbance is induced in grid through the injection of active power. The testbed uses proprietary software where access to source code or customization possibilities are sometime limited; thus affecting the usability of testbed.

Bian *et al.* [BKP+15] presents another real-time co-simulation platform for the preference analysis of a distribution automation applications in the Smart Grid. Commercial power system simulator, RT-LAB along with OPNET Modeler is used for power and communication system simulation respectively. A custom Java application is used as controller for voltage level monitoring and control of devices. SITL (system-in-the-loop) module from OPNET Modeler provides message exchange interface between the two simulators and Java control application. Results for communication impact on a simplified distribution automation system are presented.

Palmintier *et al.* [PLC+15] presents a hardware-in-the-loop co-simulation environment where components are geographically apart. IEEE 123 and 8500 node test feeders are used to study the impacts of photo voltaic (PV) inverters. The environment uses GridLAB-D for power system modeling along with PV hardware. A custom JASON-based protocol is used for connecting GridLAB-D with rest of the co-simulation environment. However, due to it ability to spread co-simulation components geographically apart, the environment imposes additional constraints like communication bandwidth, latency and processing delay etc. Also, since GridLAB-D can not use a step size lower than 1 *sec*, which also limits the granularity of real-time simulation.

Other Approaches

This subsection presents an analysis from literature for many customized co-simulation approach for the Smart Grid analysis. These approaches, usually, are employing custom interfaces for simulator coupling. Such interfaces are although more tailored towards a specific problem and thus provides more freedom and flexibility, but unlike standards (HLA or FMI) requires more work and details to be handled.

An integrated hybrid modeling and simulation approach for the Smart Grid is presented in [NKM+07, NKS+08]. Communication modeling is done with ns-2 while ADEVS is used for all the other components. ADEVS models are encapsulated into ns-2's `TclObject`. This object then gives ns-2 control over ADEVS simulator when used in an ns-2 model. A simplified model of IEEE 17-bus system is used as an example system. The approach does not utilize any domain specific tool for both the power and the control system, making it less suitable for a detailed analysis of the Smart Grid.

Monti *et al.* [MCC+09] presents a co-simulation environment for design and simulation of medium voltage DC protection management system. The environment consists of Virtual Test Bed for power system simulation, MATLAB/Simulink for reconfigurable control and OPNET Modeler for the communication system modeling. However Virtual Test Bed simulation do not participate in co-simulation. It is used to generate C code for the modeled power system; the code is than integrated into MATLAB/Simulink. The time-stepped simulation is controlled by OPNET Modeler that call MATLAB/Simulink APIs. Another environment using OPNET Modeler for wide-area communication in power system is presented in [Ton10].

A framework for the Smart Grid coordinated co-simulation is presented in [ASSC11]. Different domain specific tools are utilized for modeling power and control components of the Smart Grid. The power system network is modeled and simulated in DIgSILENT PowerFactory while MATLAB/Simulink is used for control and storage device modeling and simulation. However, the effects of communication are not considered and thus no real communication simulator is integrated into framework. The effectiveness of the framework is shown on a real Austrian residential low voltage network. Another co-simulation architecture utilizing the same tools is presented by Kupzog *et al.* [KDF+12] for the Smart Grid analysis.

Another framework (VPNET) using Virtual Test Bed power system simulator and OPNET Modeler is presented in [LMLD11]. It is aimed at providing a framework for analyzing communication channel effects on underlying power system. Both participating simulators are connected through a custom simulation coordinator written in C#. It runs the co-simulation using the fixed time-stepped approach. Since, no domain specific simulator for controller simulation is used, the framework is unable to provide insights in these regards. An extension of this framework with capabilities for MAS simulations is presented in [LLZ+13]. The framework is further used in [SLF+13] and another layer of real-time simulation is added by using RTDS [232] commercial power system simulator and a WANem [236] communication network simulator.

Global Event-Driven Co-Simulation Framework (GECO) presented in [LVS+12], aimed at wide-area monitoring and control applications in the Smart Grid. The simulation coordinator maintains a global even-queue for storing the events from two coupled simulators. For power system modeling, Positive Sequence Load Flow (PSLF) simulator is used while communication modeling is performed in ns-2. The provided framework do not have any control simulator and thus could only be used for some specific scenarios with control system.

Another co-simulation environment based on GridLAB-D and ns-3 for the Smart Grid applications is presented in [FCD+13]. Power system simulation is performed with GridLAB-D while ns-3 is used for communication network modeling. The simulators are connected through a middleware and are running independently from each other. The middleware provides time synchronization and simulation control using simple message count mechanism. The environment do not provide any control system simulation, limiting the details of analysis it could provide for a Smart Grid application.

Palensky *et al.* [PWSE13] presents an environment for the simulation of demand-response in the Smart Grid. It is realized by using GridLAB-D coupled with DIgSILENT PowerFactory and OpenModelica [227] where GridLAB-D is overall coordinating the simulation. A battery model constructed with OpenModelica is coupled with GridLAB-D using FMI while GridLAB-D is used to simulate electrical vehicles and charge management component. The DIgSILENT PowerFactory is used to simulate the distribution grid. Although two power system simulator are used but with completely different purposes. The environment provides capabilities of configuring the simulation for different level of details. A dynamic demand response example for intelligent electric vehicle charging is used to demonstrate the effectiveness of proposed co-simulation method.

Python based Mosaik framework [SST11, RLS+13] provides co-simulation with exiting simulators through a set of API (Application Programming Interface). Every participating simulator has to define an interface for communication through this set of API. It has been used in many co-simulation works; some of selected works can be found in [BCK+14, RWM+14, LNR+15, DKF+15]. Mosaik, presently do not support real-time simulations.

Stifter *et al.* [SWA+13] presents a co-simulation environment for simulating a smart charging local control strategy in the context of electric vehicles. GridLAB-D is the simulation master while MATLAB/Simulink toolbox PSAT is used for power system analysis. For control simulation, 4DIAC is used and batteries are modeled in OpneModelica. No communication simulation is provided in the presented environment.

A co-simulation environment using OMNeT++ and OpenDSS, aimed at design and analysis of wide-area monitoring applications in the Smart Grid is presented in [BAS14]. Simulation runs in a configurable fixed time-stepped values. For interfacing between the two simulator, a module is developed in the OMNeT++. This module than connects to OpenDSS using its COM interface. State estimation, voltage monitoring and renewable energy integration applications are implemented using this environment. However, the environment do not provide any control system simulation capabilities.

FNCS is proposed in [CDF+14] for power system and communication network co-simulation in the Smart Grid. It allows for simulating both transmission and distribution levels of power system in GridLAB-D and PowerFlow simulators. Communication simulation is done in ns-3. The approach is influence by HLA and used some of it concepts. A centralized broker is responsible for the overall control of the simulation. It implements a publisher-subscriber mechanism over TCP sockets using the ZeroMQ library. A time synchronization mechanism, that prediction the need for data exchange between the simulators in employed. Due to non-availability of any control system simulation, the environment can not be used for application where controller behavior analysis is also required.

Faruque *et al.* [FA14a] presents a model-based methodology for modeling and simulating a residential microgird. Considering the microgrid a Cyber Physical Energy System, GridLAB-D is used to model *physical* (power system) while *cyber* (control) modeling is done with MATLAB/Simulink. GridMat [FA14b], a MATLAB toolbox, works as the co-simulation coordinator. GridLAB-D and MATLAB/Simulink communicate with GridMat over TCP/IP sockets using HTTP protocol. Some test cases for voltage control and demand response on an IEEE 13-node system with 1000 residential customers as in a microgrid is used to demonstrate the co-simulation. For the *cyber*, the proposed methodology only provides the modeling and simulation of the control but not for communication, which make it applicability limited.

Tariq *et al.* [TSN+14] presents a co-simulation environment based on ns-3 communication and PowerWorld power system simulators. PowerWorld is integrated into ns-3 through a newly developed module. This module communicates with PowerWorld over COM interface provided by `SimAuto` add on. Two other ns-3 modules are used to represent the cyber and physical (sensor, actuator) systems. Result from a demand-response application simulated on the environment are presented. The lack of any control system simulation makes is less attractive for the Smart Grid applications where controller behavior analysis is also needed.

Another co-simulation environment for power distribution system and communication network in the Smart Grid is presented in [ARNE15]. MATLAB/Simulink is used for power system simulation while ns-3 is used for communication network simulation. A mediator is responsible for interfacing the two simulators but its composition and interfaces are not discussed. The mediator passes messages between MATLAB/Simulink and ns-3; only one of the simulation is running at a time. Resulting long simulation runtime is remedied with advance execution but this sometimes requires a rollback.

For the analysis of the custom Smart Grid solution properties, Bytschkow *et al.* presents a co-simulation framework in [BZD15]. AKKA Java toolkit is used for modeling communication components; GridLAB-D is used as power flow modeler. An open source SCADA simulator: EclipseSCADA is used to simulate a SCADA system behavior.

A microgrid co-simulation framework is presented by Kounev *et al.* [KTL+15] based on OMNeT++, MATLAB/Simulink and Adevs. Communication system modeling is done with OMNeT++ while power system modeling is carried out in MATLAB/Simulink. Coupling between the simulators is provided by Adevs's atomic modules. The synchronization mechanism is based on a dynamic time stepped scheme and only one of the two simulators are active at any give time. Results from a medium voltage DC Microgrid with 5 MW wind-turbine local sources are presented. However, the synchronization scheme could introduce unnecessary long runtimes and may require a rollback that is not supported.

3.4 Requirements

Figure 3.9, presents an overview of requirements for a co-simulation based tool-set towards fulfilling the aims of this work. The Smart Grid is a multi-domain system where different domain experts are involved in the research and development process. Modularity and extendability are, therefore, necessary requirements to enable these domain experts to use a tool of own choice and expertise for modeling/simulation of respective domain. The requirements are, further, influenced by the control and the power system simulation requisites. The control system simulation, usually, investigates embedded, centralized and distributed controllers. Similarly, different time scales can be considered when investigating the power systems through simulations. Additionally, running the simulation in real-time not only enables the possibility of a hardware-in-the-loop simulation but further simplifies it by not requiring a simulation synchronization mechanism. To provide such a co-simulation based tool-set, useful in most of these cases, is envisioned with the following set of requirements:

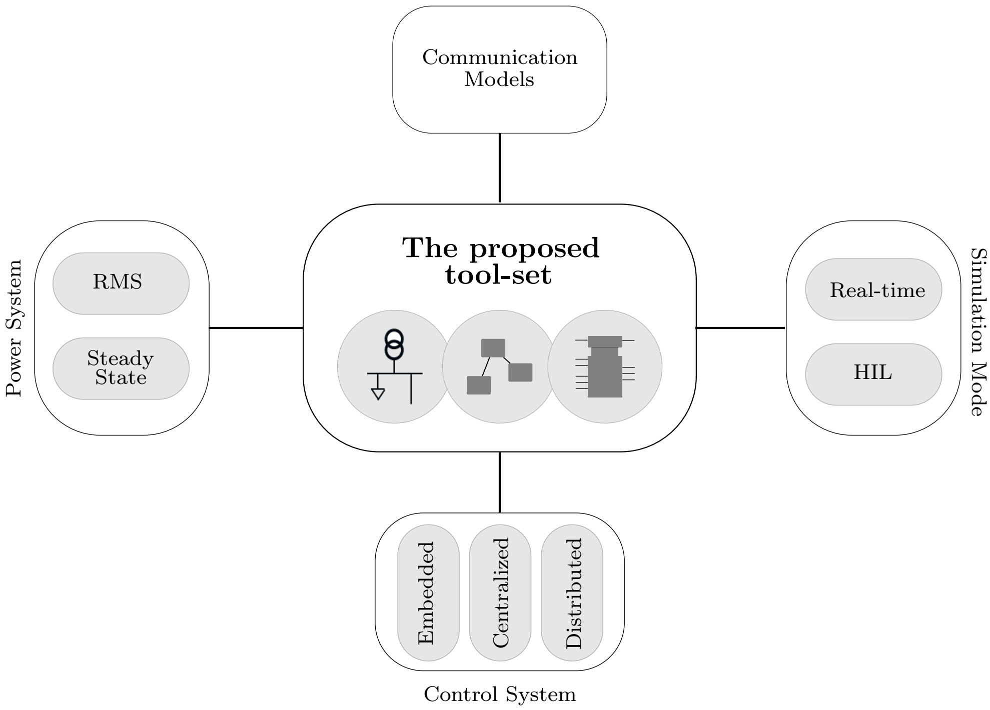


Figure 3.9: Requirements for a co-simulation based tool-set to achieve the aim of this dissertation.

- R_1: Modular simulation component for power, communication, and control systems
- R_2: Support real-time and hardware-in-the-loop simulations
- R_3: Support embedded, centralized and distributed control applications
- R_4: Support various time scales for the power systems simulations
- R_5: Support diverse Smart Grid communication infrastructure models

The Figure 3.9 depicts these five requirements graphically. The proposed tool-set is expected to be modular (R_1), as shown with the box in the middle, supporting the major domains including power, communication and control for the Smart Grid investigations. The "Communication Models" represents that it supports divers communication infrastructure models with varying parameters, scenarios and technologies (R_5). The "Simulation Mode" specifies that it will enable a real-time and hardware-in-the-loop simulation executions (R_2). It will support power system simulation in electromagnetic transients with timescales in milliseconds to seconds and steady states with timescales in seconds and above for the power system dynamical simulations (R_4). Three different types of control system simulation are addressed in the proposed tool-set namely embedded, centralized and distributed (R_3).

4 Methodology

In the previous chapter, the Chapter 3, a detailed analysis of literature regrading modeling and simulation of the Smart Grid is presented. Additionally, a set of requirements for a tool-set capable of providing co-simulation of diverse Smart Grid applications are identified. In this chapter, an analysis methodology is described that will be used with the proposed tool-set for the investigation of communication infrastructure models for diversion Smart Grid applications.

4.1 Overview

After analyzing the literature in previous chapter and providing some requirement in Section 3.4 for tool-set, this section presents an overview of the adopted methodology to provide an analysis of communication infrastructure using the tool-set, capable of fulfilling the identified requirements and to answer the research questions, presented in Section 1.2.

Figure 4.1 shows a view of the Smart Grid subsystem dependency. Power system operations are controlled through the *Control system* that is further dependent on the *Communication system* for providing, e.g. measurements from *sensors* and for delivering commands to *actuators*.

A graphical representation of the methodology is depicted in the Figure 4.2. As can be seen, the methodology is divided into three phases, namely; *modeling*, *simulation* and *analysis*. In the modeling phase, a Smart Grid Application under Test (SGAuT) is modeled. The model consist of power system and control models, communication scenarios and identified key performance indicators (KPIs) of interest. In the simulation phase, *simulation scenarios* are generated, first, and then are co-simulated using the proposed co-simulation based tool-set. The generated results, after co-simulation, are analyzed in the analysis phase. A feedback loop from analysis to modeling phase indicates a possibility of incorporating the identified results into models. A more detailed description of individual phases is described below.

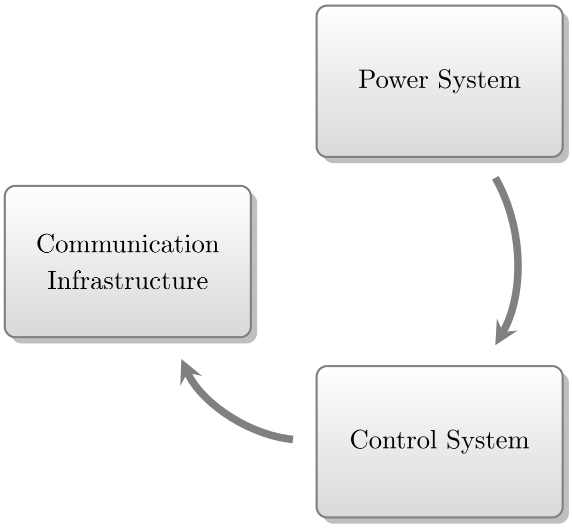


Figure 4.1: Sub-system dependency in the Smart Grids. Power subsystem is controlled by control subsystem, which depends further on the communication subsystem for, proving measurement from sensors and delivering command to actuators.

4.2 Modeling Phase

In the modeling phase, the Smart Grid Application under Test (SGAuT) is modeled with its identified power system, communication and control components. For communication infrastructure, varying communication scenarios, representing different technologies, parameters, failures and channel sharing can be specified. These scenarios are later translated into communication models for co-simulation. Additionally, some key performance indicators are needed to be specified for the quantification of results. An example output from a completed modeling phase can be seen as in Figure 4.3.

4.2.1 Power and Control System Models

As a part of the communication infrastructure analysis, the power system component of SGAuT are needed to be modeled. This modeling can be done with any domain specific power system simulator.

Similarly, control modeling needs to be done as it constitute an important component of SGAuT. It is possible, for example, to either use a domain specific modeling tool like 4DIAC, MATLAB/Simulink etc. or use a general purpose programming language like Python etc.

4.2.2 Communication Scenarios

Communication Scenarios are used to specify communication parameters like technology, bandwidth, latency, protocol etc., combination of which could be used to translate into communication

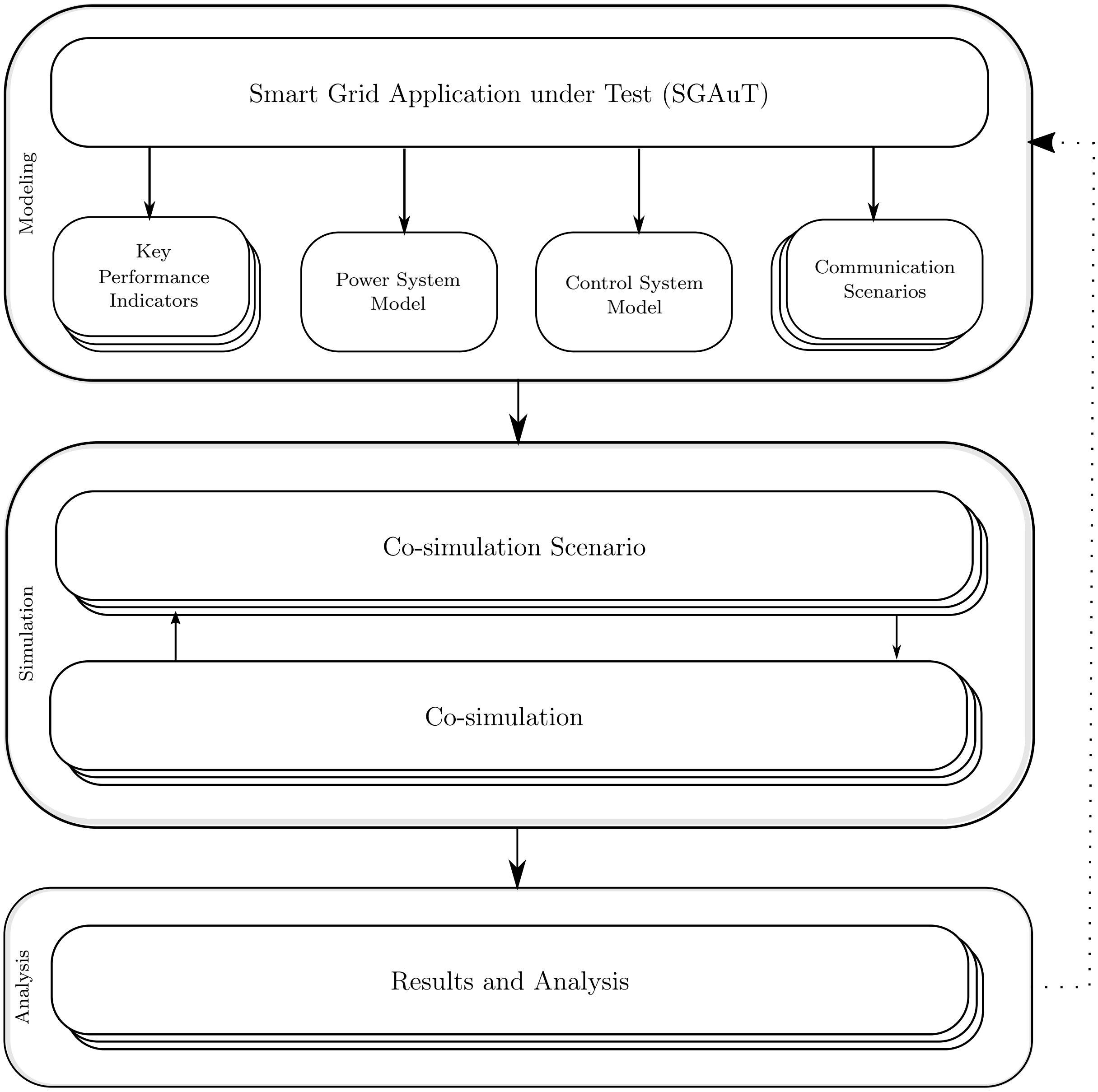


Figure 4.2: Overview of the methodology. It is divided into three phases; modeling, simulation and analysis.

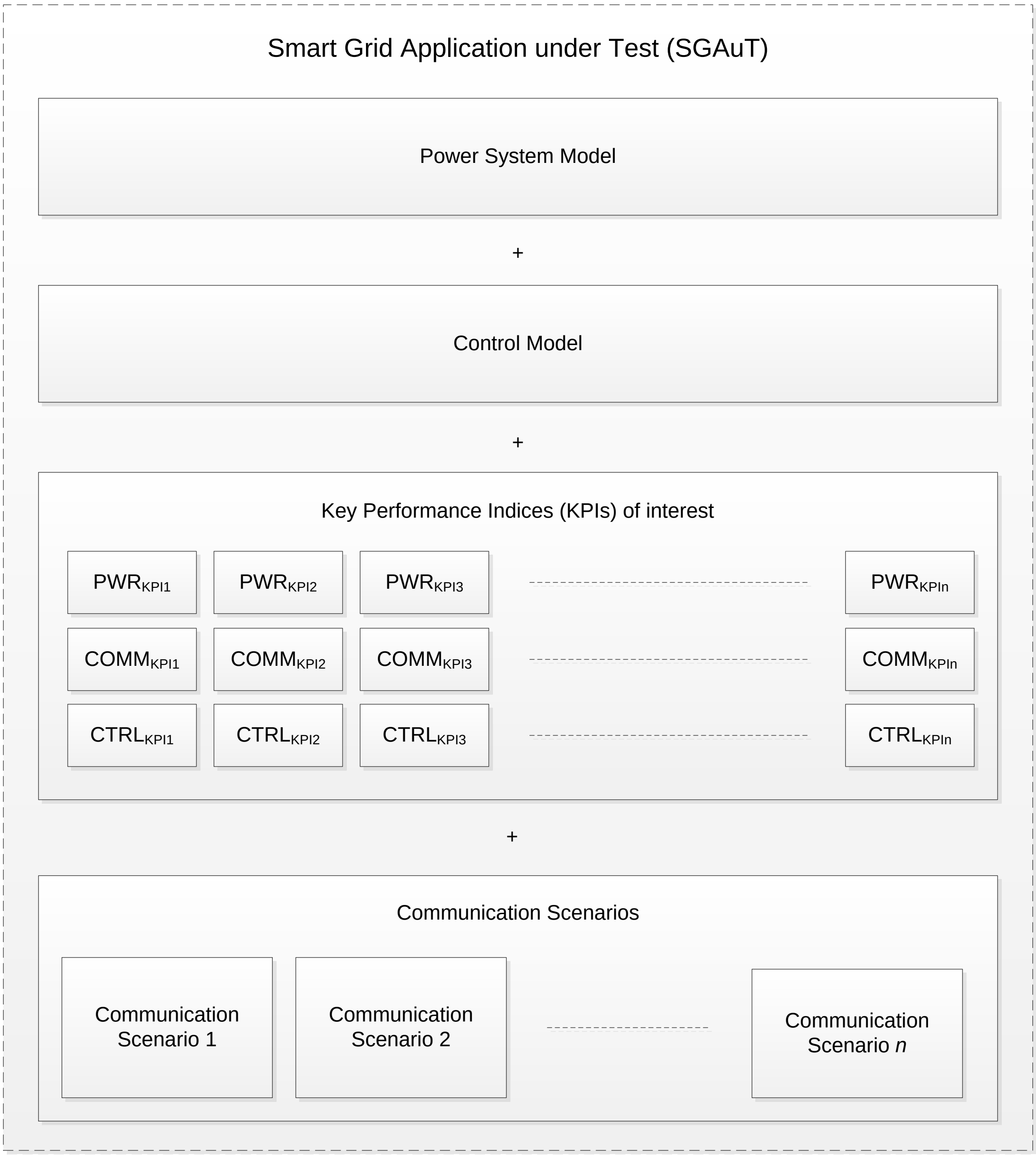


Figure 4.3: A example outcome of the *modeling* phase for a SGAuT.

infrastructure models. These models are then co-simulated along with power and control domain models to evaluate system perform under these communication infrastructure models. Table 2.5, e.g., can be used as a general guideline for selecting the communication characteristics for a SGAuT. These characteristics can later help in selecting the communication parameters, e.g., from the Table 2.4.

4.2.3 Key Performance Indicators

Using key performance indicators (KPIs) to measure the performance has been a standard practice. A KPI can be defined from some system measurements to assess performance. In the European context, European Electricity Grid Initiative (EEGI) [207] provides a KPIs based common reference framework for the performance evaluation of a Smart Grid solution. Stakeholders like DSOs, TSOs and the research entities have contributed to EEGI framework with sharing their experiences of working on the European Smart Grid projects. This framework is particularity focused on common and suitable methods for performance evaluation of such projects.

Mostly influenced by EEGI framework, the European Smart Grid projects like GRID+ [212], IGREENGrid [219], IDEA4L [216], Grid4EU [213] etc., have defined a comprehensive list of KPIs for the assessment of different aspects (real-time monitoring, voltage and power quality, energy loss reductions, etc.) of a given Smart Grid application's performance. For results quantification, these KPIs can be specified for any of the subsystem model. However, the choice of KPIs is high depended on the underlying application.

4.3 Simulation Phase

Once, the modeling of power system, control and communication scenarios is done, and KPIs for calculation are specified, the co-simulation can be performed. This phase is divided into two sub-phases; co-simulation scenarios generation and co-simulation. Figure 4.4 shows a flowchart for this phase. It starts with the creation and simulation of reference scenarios (Best Case and the Worst Case) with ideal and no communication assumed. It then iterates over all the provided communication scenarios, creating and simulating each of them. When there are no more scenarios, recorded data is used to calculate KPIs.

4.3.1 Simulation Scenarios Generation

This sub-phase first generates communication models and then integrates them with power system and control models, provided in the modeling phase, to create co-simulation scenarios, iterating over all the communication provided scenarios. These two processes are explained in Figure 4.5 and Figure 4.6.

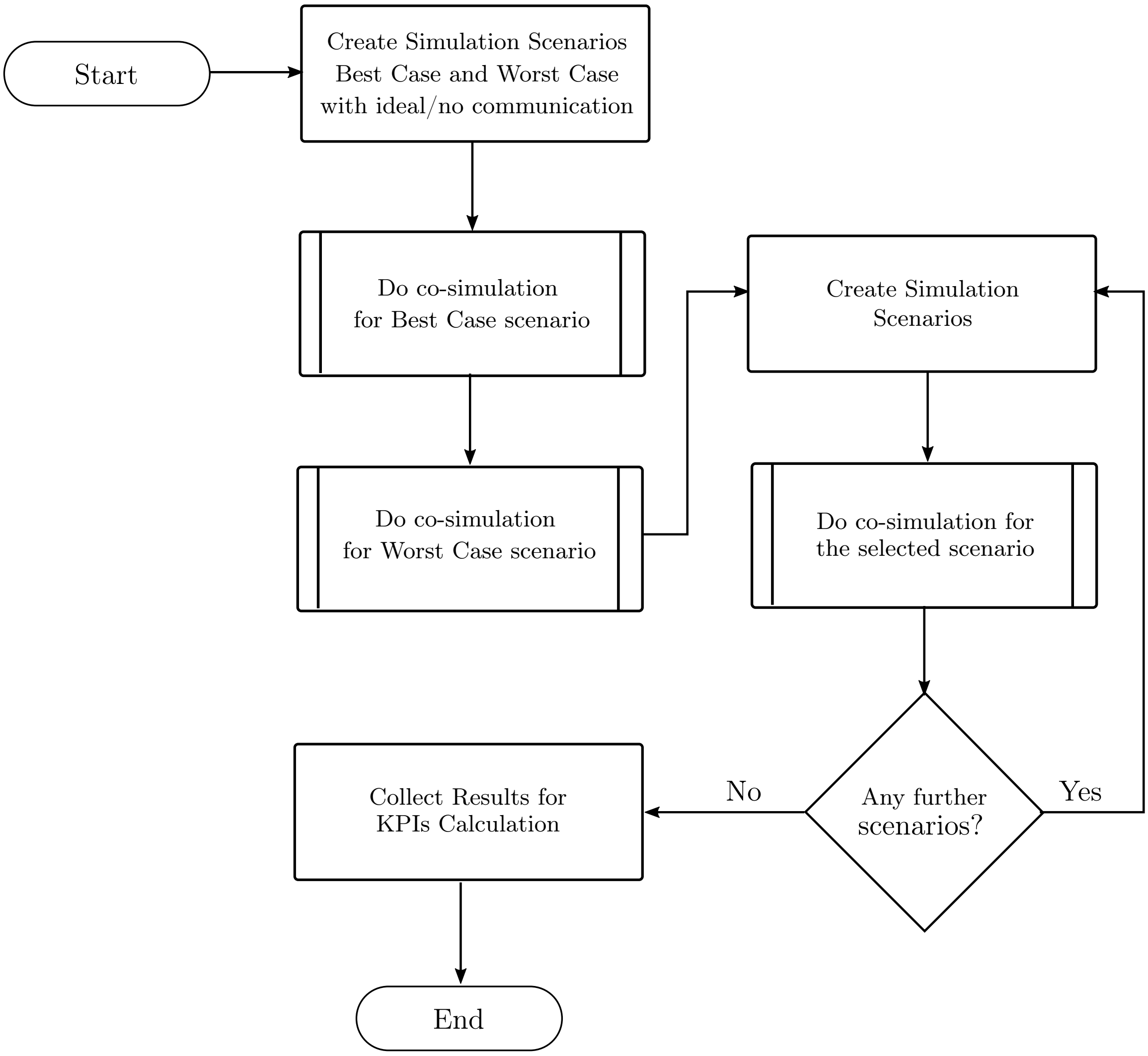


Figure 4.4: The (co-)simulation phase. It starts with the creation and simulation of reference scenarios (Best Case and Worst Case) with ideal and no communication assumed. It then iterates over all the provided communication scenarios, creating and simulating each of them. When there are no more scenarios, recorded data is used to calculate KPIs.

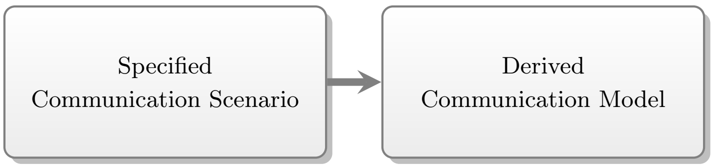


Figure 4.5: Communication models are generated from provided communication scenarios.

Once the communication modeling for all the specified communication scenarios is done, a simulation scenario is created with taking the modeled communication scenarios one by one along with the power and control system models.

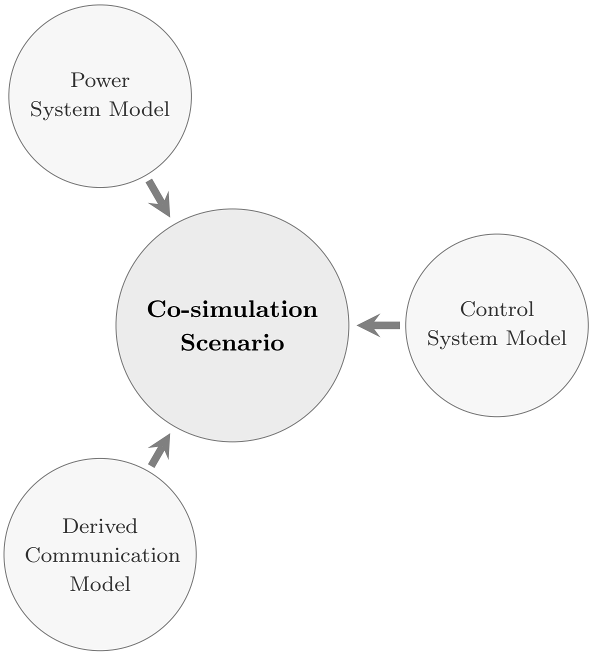


Figure 4.6: A co-simulation scenario is generated from derived communication model for each communication scenario provide, along with power and control system models

4.3.2 Co-simulation

Once the Co-simulation Scenario are ready, it could be co-simulated. The co-simulation also get the key performance indicators to be calculated during the co-simulation. This process in expressed in Figure 4.7.

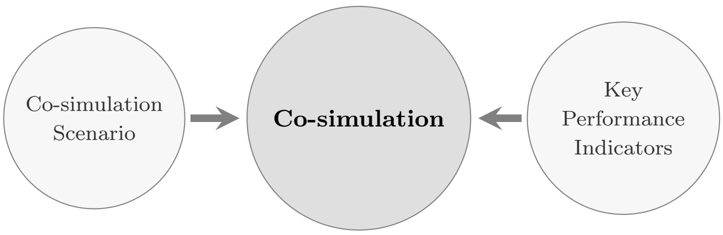


Figure 4.7: The co-simulation sub-phase, takes a simulation scenario and KPIs.

4.4 Analysis Phase

The analysis phase calculates the specified KPIs from the results of individual co-simulation scenario results. Once, co-simulation of a scenario is completed and results are collected, the analysis can be performed on the collected results to calculate the key performance indicators. An overview of the process is depicted in the Figure 4.8.

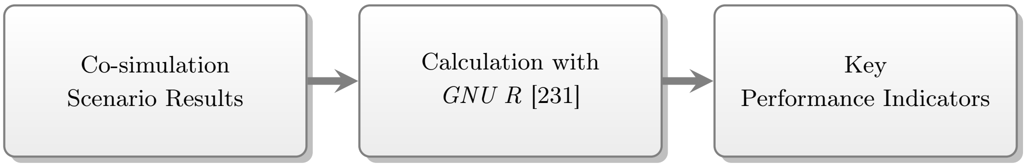


Figure 4.8: The Simulation phase. After simulating the base-case with ideal communication, iterates over the defined Communication Scenarios and simulates them.

5 Case Study I – Voltage Regulation in a Low Voltage Network with high penetration of Photovoltaic systems and Electrical Vehicles

After a detailed description of the methodology in previous chapter (Chapter 4), this chapter presents the first case study addressing voltage regulation problem in a low voltage network. Varying communication infrastructure models and scenarios are analyzed for this Smart Grid innovative solution implemented with an IEC 61499 based embedded controller. The co-simulation environment consists of power system dynamic simulator DIgSILENT PowerFactory, communication simulator OMNeT++ and IEC 61499 runtime environment FORTE. Figure 5.1 highlights the identified requirements addressed in this case study (RMS power system simulation, embedded controller, real-time simulation control).

The chapter begins with Section 5.1, describing background of the voltage regulations problem addressed in this case study while suitability and case study design is presented in Section 5.2. Section 5.3 describes the modeling of the power and control system and key performance indicators. Section 5.4 presents the reference and modeled communication infrastructure models and scenarios. Co-simulation concept, simulation tools and simulator coupling are described in Section 5.5 while Section 5.6 presents and analyzes the results for individual simulation scenarios. The chapter concludes with a summary in Section 5.7.

5.1 Background

Electrical power system is transforming rapidly in structure and functionality under the vision of Smart Grid. As discussed in the Chapter 2, this transformation is influenced by many technological, economical and environmental factors. Greenhouse gas (GHG) emission from traditional power generation plants has been a major concern as it effects the environment. Finding clean and green power generation sources with low GHG footprints has been an active motivation towards

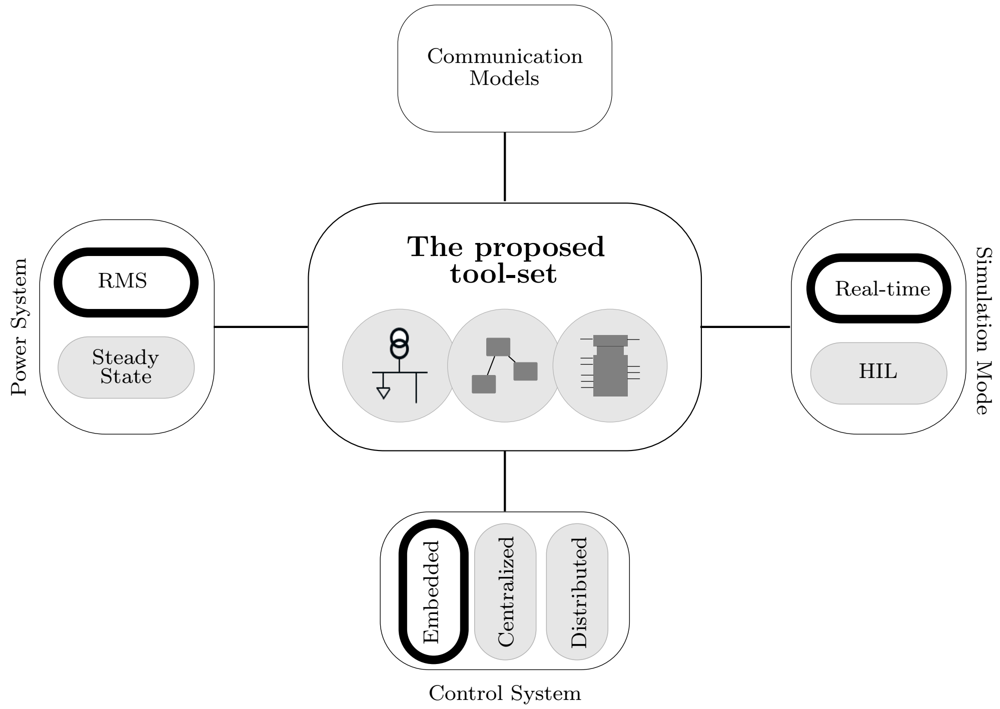


Figure 5.1: Parts of requirements addressed in co-simulation environment for this case study.

Smart Grid. Renewable energy resources such as the photovoltiac systems (PVs), wind, biomass etc., for power generation are much "clean and green" than, for example, fossil fuel based traditional power generation methods (see Figure 2.2). Additionally, due to relatively small size, these generators can be distributed around the load centers reducing the transmission losses. Electrical Vehicles (EVs) can also contribute towards reducing GHG and providing cleaner transportation means as compared to conventional vehicles [BDT14]. Smart Grid enables the use of EVs both as the load and as an energy source, when needed.

Although, increased hosting of distributed energy resources (DERs) and EVs can increase the flexibility and reliability of power system but posses many technological challenges due to the intermittent nature and problem in accurately forecasting the generation of these resources. Among these challenges are voltage regulation and power quality maintenance [SAK+15, ELKB12]. The voltage fluctuation could be large due to, for example, PVs generation and EVs charging (load). Increased monitoring and control could help in ensuring the power quality and keeping the voltages under limits as defined in standards such as EN 50160. This requires deployment of considerable number of sensors and actuators in the network. However, such monitoring and control relays on the communication infrastructure for transmitting measurements data and commands (Figure 4.1). These factors make it necessary to analyze communication infrastructure before deploying into the field.

In this case study, voltage regulations in a low voltage residential network having photovoltiac systems and electrical vehicles is addressed where an OLTC transformer is used for voltage regulation, through an IEC 61499 based remote controller. The controller calculates and sends new tap position to OLTC transformer after receiving measurements from the network. This makes the control actions highly dependent on the communication infrastructure and its performance. This case study addresses the need and provides an analysis with the simulation of different popular communication technologies, failures and channel sharing scenarios. Some the key performance indicators such as the voltage violations and the variations, and the communication delay, are calculated for each simulation scenario.

5.2 Suitability and Design

To provide the analysis of communication infrastructure, the analysis methodology is applied to this case study. The case study uses a IEC 61499 based embedded controller and is selected to show the effectiveness of the proposed tool-set for such Smart Grid applications. The power system model represents a low voltage rural 0.4 kV residential network where an OLTC transformer is used to regulate the voltage through a coordinated remote voltage controller. The remote controller is connected to the sensors and OLTC transformer through a communication infrastructure. Based on the received measurements from the network, the controller then calculates new tap position, if required, and send it to OLTC transformer using the same communication infrastructure. The control actions are, therefore, highly dependent on the performance of the underlying communication infrastructure.

There are number of different communication technologies (Table 2.4) enabling many possibilities for the implementation of a communication infrastructure. Further, each technology has its own characteristics and performance that may or may not match with the specific deployment requirements. A tool capable of investigating the alternative technologies is therefore, highly valuable to access the performance of system under different communication parameters. It is also helpful to see how some communication failures could affect controller performance along with its effects on the underlying power system. Similarly, sharing a communication channel with multiple application and services would also be of interest as it may not be feasible solution to use a dedicated communication infrastructure for every other deployed application in the same or neighboring network. The communication infrastructure investigation is, therefore, divided into three categories. In the first category, different communication technologies (wired, wireless and Powerline communication) while in the second, communication failures are addressed, and the third category consists of communication channel sharing scenario. As proposed in the methodology, key performance indicators are used to measure and quantify the effects of different communication infrastructure scenarios.

This case study is selected for the analysis of its IEC 61499 based embedded control system performance under varying communication infrastructure models and its effects on underlying power system. It will help in showing the effectiveness of proposed co-simulation based tool-set in analyzing RMS power system simulation, embedded controller, real-time simulation control (Figure 5.1) in a Smart Grid solution.

5.3 Modeling

Modeling is the first phase of the methodology (Figure 4.2). In this phase, power and control system are modeled and the communication scenarios are specified. Dedicated domain specific tools are used for modeling power and control system. In this case study, power system modeling is done in DIgSILENT PowerFactory while control algorithm is implemented in 4DIAC-IDE using IEC 61499 reference model for distributed automation.

5.3.1 Power System

The electrical power grid needs to be modeled for the use in the proposed co-simulation, where communication infrastructure using different scenarios are to be evaluated. The power system modeling is carried out by using the commercial power system simulator DIgSILENT PowerFactory [205].

Figure 5.2 shows a low voltage rural 0.4 kV residential network with high penetration of PVs and EVs modeled in DIgSILENT PowerFactory. It consists of 3 feeders with lengths between 200 and 250 meters. There are 13 loads representing households in addition to 9 PVs and 5 EVs. PVs generation increases the voltages while EV charging decreases the voltages on the connected bus. Sensors are deployed on the critical buses identified previously through simulations. An On Load Trap Changing (OLTC) transformer is used to regulate the voltage through a coordinated remote voltage controller. The remote controller is connected to the sensors and OLTC through a communication infrastructure. Based on the received measurements from the network, the controller calculates new tap position and send it to OLTC using the same communication infrastructure. The control action is therefor highly dependent on the performance of underlying communication infrastructure.

5.3.2 Control System

IEC 61499 reference model for distributed automation [217] is applied for the modeling of the control system. The IEC 61499 provides a component-oriented, hierarchical approach for modeling distributed systems. In this approach, virtual event based software units encapsulating data and behavior and called functional blocks are used as the basis for developing reusable modules. There are three different kinds of functional block in IEC 61499 namely Basic Function Block, Composite Function Block and Service Interface Function Block. The basic function block is used to model the basic data and events and its behavior is controlled by a stat machine called execution control chart (ECC). Composite functional blocks can be used to encapsulate a network

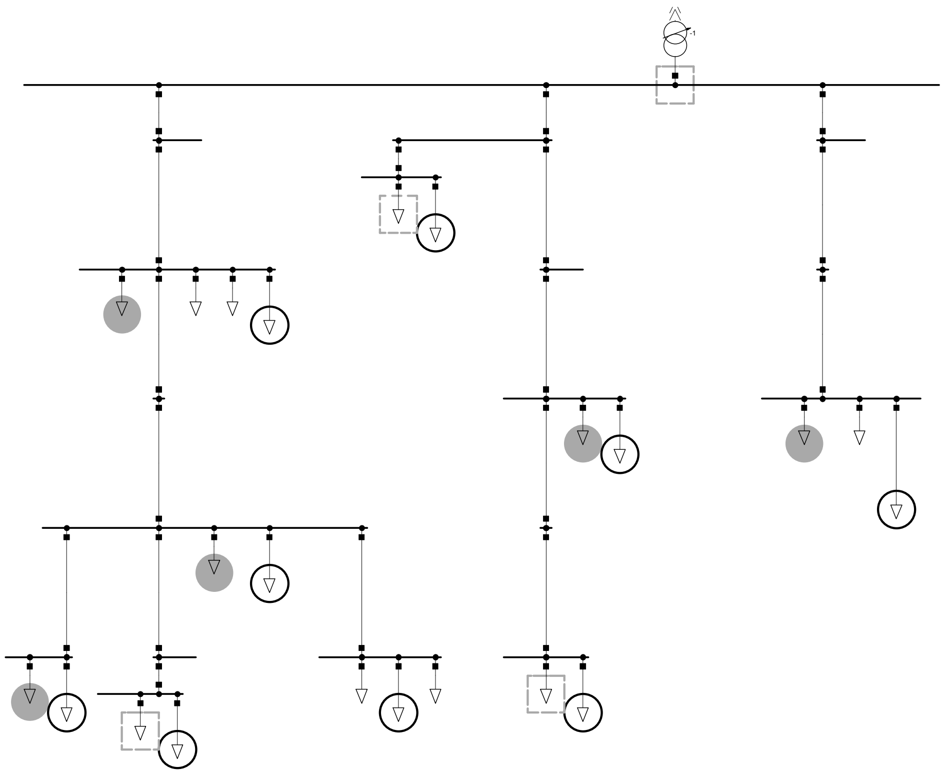


Figure 5.2: The power system of the case study modeled in DIgSILENT PowerFactory. In the model, the photovoltiac systems are identified with black outlined circles, the electrical vehicles with gray filled circles and the measurement units with gray rectangles.

of basic functional blocks while the service interface block provide interface between application and execution platform. According to IEC 61499 vocabulary, a device is defined as a programmable controller while as resource is defined as a network of different functional blocks. A resource can be assigned to a device and a system consists of a number of devices [LHY15].

In any IEC 61499 function block implementation, a runtime environment is required for the dispatch of events between the function block for execution. The implementation, therefor, needs to be compiled with appropriate run-time environment. The runtime environment generates the code that is appropriate for the execution on the chosen platform [LHY15].

Figure 5.3 shows the control model implemented in 4DIAC-IDE environment. The model consist of a network of function blocks. 4DIAC-IDE has a companion runtime environment FORTE that is used to compile the implemented model for later execution in the proposed co-simulation. The runtime system is capable of execution on numerous platform including embedded systems and on PC.

As can be seen in Figure 5.3, there are five function blocks in the control model. The function block `CalculateUmaxUmin` calculates the minimum U_{min} and maximum U_{max} voltages from the measurements received. The calculated U_{min} and U_{max} are passed to `TapChangeAlgoritm` function block. It then uses these values to calculate the new tap position, when required.

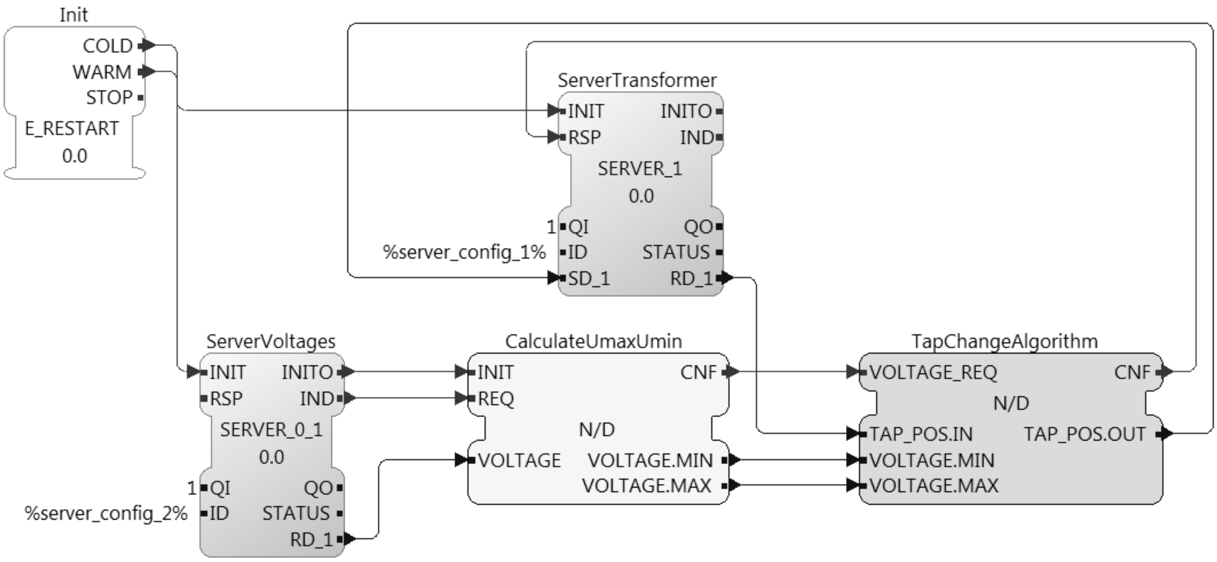


Figure 5.3: Control system algorithm modeled in open source 4DIAC-IDE environment using the IEC 61499 functional blocks. The model consists of a network of different basic functional block each performing a dedicated task and connected to provide input or receive output to perform the steps of the algorithm. The function block `CalculateUmaxUmin` calculates the minimum and maximum voltages from the measurements received while `TapChangeAlgoritm` function block calculates the tap position based on the input from `CalculateUmaxUmin`.

5.3.3 Key Performance Indicators

Key Performance Indicators (KPIs) are used to measure and quantify the results between different communication scenarios. For this case study two KPIs are specified for calculation from the power system. These KPIs are adopted from EU Smart Grid project IGREENGrid [219]. The KPIs measures the voltage deviations on selected buses with respect to the Best Case.

Voltage variation KPI is defined as:

$$V_t^{variation} = V_t^{BaseCase} - V_t^{Scenario} \tag{5.1}$$

Where $t = 0, ..., SimTime$

The calculated $V_t^{variation}$ is interpreted as:

$$V_t^{variation} \begin{cases} \text{Variation is towards upper side;} & > 0 \\ \text{Variation is towards lower side;} & < 0 \\ \text{No variation} & 0 \end{cases} \tag{5.2}$$

For a certain bus i the Voltage Violation KPI is defined as:

$$V_i^{voilation} = \sum duration[V_i^{max} < V_i < V_i^{min}] \tag{5.3}$$

This KPI represents the sum of duration of bus voltage violations (time in which voltage remained out of allowable maximum and minimum limits), at a certain bus.

Although, only two KPIs are specified for this case study but the methodology is capable of calculation any number of specified KPIs of interest.

Similarly, for communication system, the chosen KPI is the communication delay. This KPI is important as it is one of the important measures that could affect the control action. The control action is dependent on the voltage measurements from the network and if the measurements are delayed, the control actions will also lag behind.

$$D = S + T + Q \tag{5.4}$$

D is the sum of times taken of a packet to be delivered at a destination. It includes service time S, propagation delay T at the physical channel and queuing time Q.

5.4 Communication Scenarios

In order to evaluated the performance of the control system and its effects on the underlying power system with varying communication technologies, parameters and scenarios of the communication infrastructure needs to be modeled. For this purpose, communication infrastructure models with varying parameters of three different communication technologies, communication failures and communication channel sharing are modeled with OMNeT++ and later co-simulated with the power and control system models.

In addition to these modeled scenarios, two reference scenarios are used to measure the best and worst performances and used later for comparisons and KPIs calculations.

5.4.1 Reference Scenarios

In the Best Case and the Worst Case reference scenarios, communication infrastructure is modeled with *ideal* (infinite bandwidth and no latency) and the *worst* (no communication possible) communication scenarios. These scenarios provide the best and the worst performances of control system and provide a measure of the communication infrastructure dependency. The Best Case scenario results are, later, used to calculate some KPIs for other communication infrastructure models including the Worst Case.

Best Case

To evaluate the true performance of control system and its effects on the underlying power system, when there is no longer any dependency on the communication infrastructure, a reference scenario with ideal communication is assumed. In ideal communication the communication infrastructure has the infinite bandwidth and negligible latency.

Worst Case

In the Worst Case, the communication infrastructure no longer allows any communication to happen between sensors/actuators and control system. This scenario is useful to see how control system responds and what effects it produces on the underlying power system, when the communication links fails. It further, allows to see the worst performance when communication infrastructure dependency is not fulfilled.

5.4.2 Modeled Communication Scenarios

For the communication infrastructure analysis, different communication scenarios are specified. These scenarios are divided into three categories based on the focus. The scenarios in the first category evaluates different communication technologies (wired, wireless and Powerline), the second category evaluates the communication failures while the third category provides analysis when the communication channel is being shared with other services. The table below (Table 5.1) provides a short description of the individual scenario and points to the communication model developed from it in OMNeT++.

5.5 Co-simulation

As part of the analysis methodology, co-simulation is used to evaluate the communication infrastructure. This section describes the concept, tools used and the developed/employed coupling interfaces for the co-simulation setup used in this case study.

5.5.1 Concept

Figure 5.4 depicts the conceptual overview of the co-simulation setup. Three separate simulators are used to simulate power, communication and control systems. The simulators are running independently without any master, in real-time synchronized with system clock.

During the simulation, power system simulator (DIgSILENT PowerFactory) simulates the power system model (Figure 5.2) and send the voltage measurements using communication model described in Section 5.4 and simulated with OMNeT++, to the control model being simulated with

Table 5.1: Communication Scenarios

Category	Name	Description	Model
Technology	Wired	Two variations of wired communication technology (Wired 40 *Gbps* and Wired 1 *Gbps*).	Figure A.1
	Wireless	An infrastructure wireless communication technology (IEEE 802.11g) where Access Points are connected with a wired communication technology having 54 *Mbps* bandwidth.	Figure A.2
	PLC	Three variations of Powerline communication (PLC 1 *Mbps*, PLC 128 *kbps* and PLC 33 *kbps*)	Figure A.3
Failures	Link Failure	Scenario where VMU_2 and VMU_4 are modeled to have failed sending measurements and receiving commands	Figure A.4 and Figure A.5
Sharing	Channel Sharing	Constant traffic of 10 *Mbps* is also going on the same data channel used for sending and receiving measurements and control commands	Figure A.6

FORTE (4DIAC-RTE) runtime. The control algorithm calculates the tap positions based on these measurements and send them back using the communication model to power system simulator. Calculated tap positions is then set in the OLTC for voltage regulations.

5.5.2 Simulator Coupling and Interfaces

Due to non-availability of native interfaces, in the co-simulation environment, the simulator coupling is achieved by using custom interfaces. Figure 5.6, shows the simulation setup with the developed interfaces while a description of individual interfaces and tools is provided below.

DIgSILENT PowerFactory

DIgSILENT PowerFactory is a sophisticated highly specialized, flexible and extendable platform for the power system modeling and simulation. It provides a combination of both graphical and scripting-based methods for almost all the major areas of the power system including generation, transmission, distribution etc. Although, a large library of models exists in the tool but it is also possible to add new models using DIgSILENT Simulation Language (DSL). For dynamic simulation of power system, the tool provides many functionalities including load and power flow calculations, reliability and contingency analysis, RMS simulations and many more. The tool also provides an application programming interfaces (APIs) that can be used to communicate

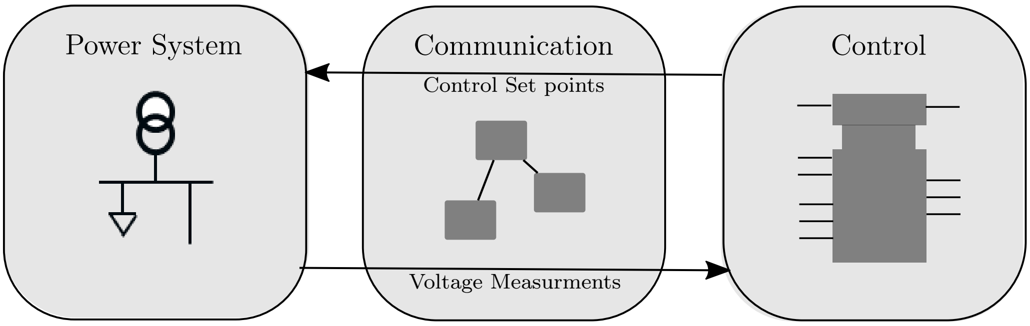


Figure 5.4: Conceptual overview of co-simulation setup. Voltage measurements are sent over communication infrastructure to control system while control set points are sent again using communication infrastructure to power system. The three participating simulators are running independently in real-time synchronized with system clock.

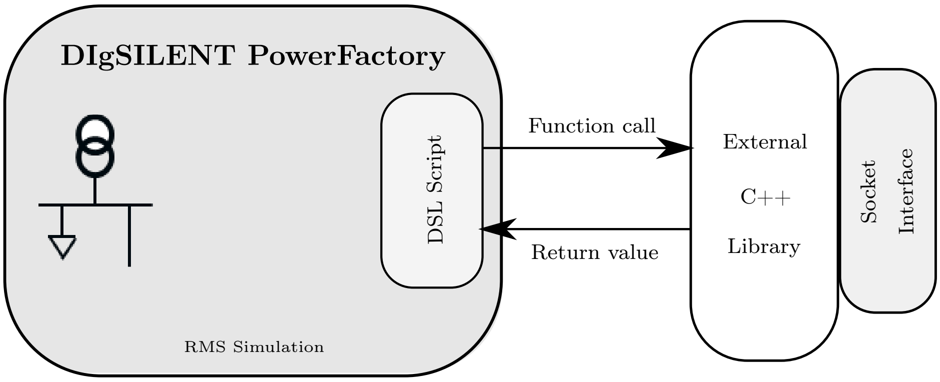


Figure 5.5: DIgSILENT PowerFactory coupling interface overview. An external C++ library is used through a DSL script to provide a socket interface. The library is invoked during the dynamic RMS simulation through function calls.

with other simulators and/or embedding the tool into other applications. It further supports the automation using DIgSILENT Programming Language (DPL) [FMGL15].

A custom interface is developed using a DSL model and an external C++ library to implement a TCP/IP socket interface. The implemented DSL model is then executed during the dynamic simulation of the power system model to send and received the measurements and control actions. The sent value are encoded using ASN.1 encoding as recommended in the IEC 61499 reference model. A schematic overview of the interface in depicted in the Figure 5.5 below.

4DIAC Framework

4DIAC [201] is a specialized open-source software environment providing a framework for modeling and simulation of IEC 61499 compliant control applications. The environment is available since 2007 under Eclipse Public License (EPL) v1.0. The framework has two main components; 4DIAC-IDE and 4DIAC-RTE (FORTE), the run-time environment.

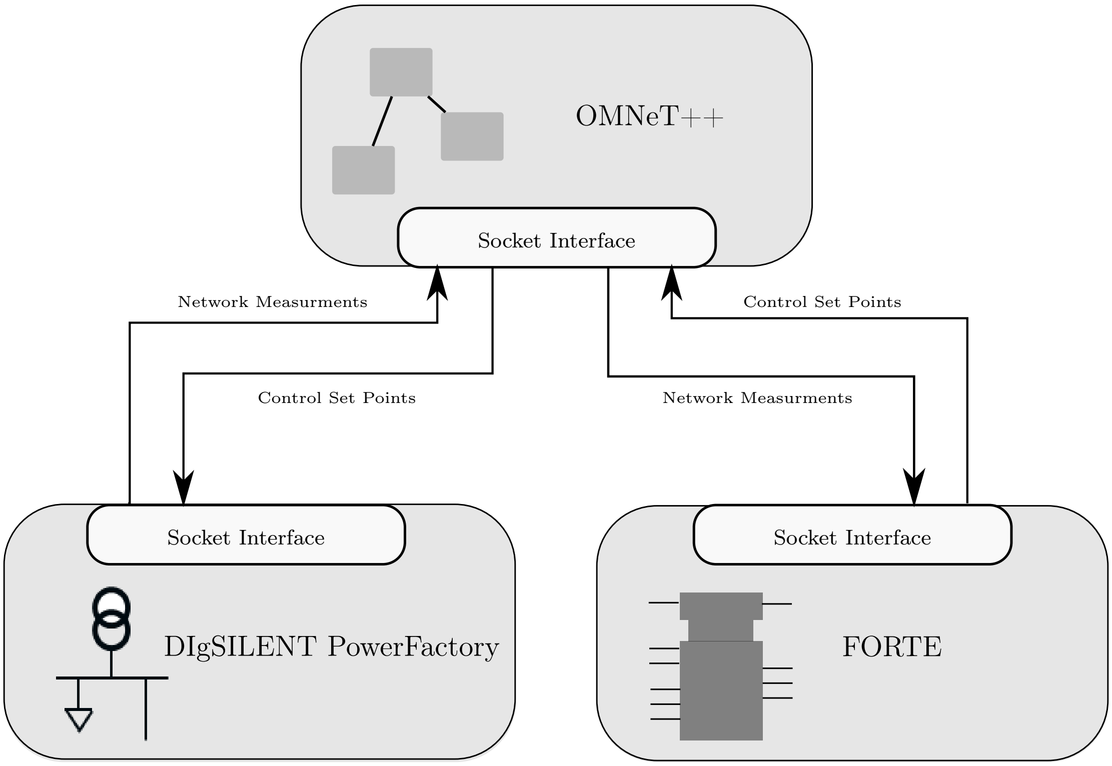


Figure 5.6: Simulation Setup. The three simulator (DIgSILENT PowerFactory, OMNeT++ and FORTE) are shown, with custom socket interfaces that are used for data exchanges. During the power system dynamic simulation (in DIgSILENT PowerFactory), network measurements are sent to communication simulator (OMNeT++) that are to be forwarded to the control simulator (FORTE). The control simulator then calculates the new control set points for OLTC and send them to communication simulator which in turn sends them to power system simulator.

4DIAC-IDE provides an Eclipse-based integrated development environment (IDE) for modeling and programming the embedded industrial controllers that are IEC 61499 compliant. The models are programed using the IEC 61499 Functional Blocks [217]. The modeled control application can then be downloaded on any 4DIAC-RTE compatible hardware, for execution.

The second component of the 4DIAC framework is the FORTE (4DIAC-RTE), a small multi-threaded portable C++ program that implements the IEC 61499 run-time environment. It can run on many hardware platforms including small embedded system and supports the execution of control programs developed in 4DIAC-IDE.

For enabling a TCP socket interface, IEC 61499 standard defined Service Interface Function Block called `CLIENT/SERVER` for generic two-way communication (Figure 5.7) is used. As can be seen in Figure 5.3, two of `SERVER` Service Interface Function Block (`ServerTranformer` and `ServerVoltages`) are used in 4DIAC model. These blocks are implemented using TCP/IP sockets and ASN.1 encoding. The socket interface is then used for voltage measurement and OLTC tap positions receiving and sending (in the case of OLTC taps).

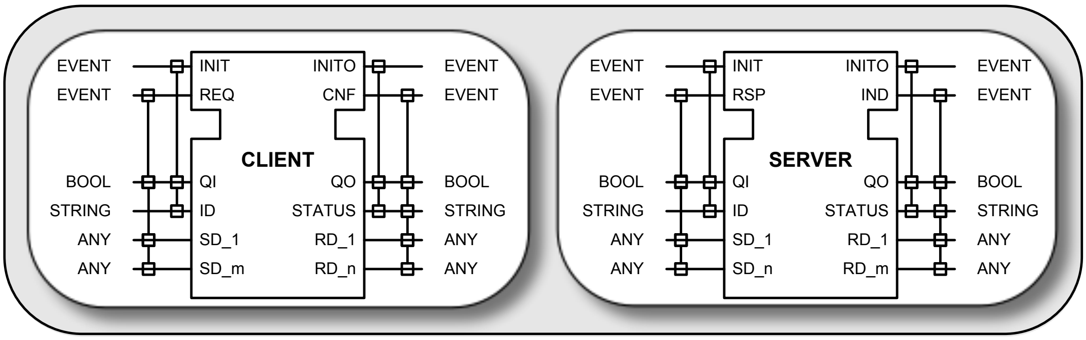


Figure 5.7: The 4DIAC control model uses the IEC 61499 standard `CLIENT` and `SERVER` Service Interface Function Block for bi-directional TCP/IP socket communication.

OMNeT++

OMNeT++ (Objective Modular Network Testbed in C++) [226] is a popular open-source discrete event simulation platform available since 1997. It is widely used for communication, multiprocessor, distributed and parallel system modeling and simulations. It is a platform that provides the basic discrete event simulation model and simulation library (simulation kernel, message passing, random number generation, statistics collection etc.) and tools (Network Description Language (NED), debugging tools, results analysis etc.). A prominent feature of OMNeT++ is its extendability that makes is very flexible for incorporating custom functionalities. Numerous models exists for OMNeT++ that provide the ability to model and simulation may popular networks, protocols, questing and files system etc.

OMNeT++ supports a hierarchical structure of modeling where the basic building block is a *module*. There are three primary types of supported modules, namely Simple/Active, Compound and System module. The simple module encapsulates basic functionality and are written in C++ along with their description in OMNeT++'s Network Description Language (NED). These simple modules can then be combined into a compound module to create more complex modules. Both the simple and the compound modules have *gates* that are used for sending and receiving *messages*. The system modules (also called a *Network*) are special types of modules that do not have gates and can be created using both the simple and the compound modules [VH08]. Figure 5.8 depicts this hierarchy of modules.

OMNeT++ is used as the communication system simulator in the proposed co-simulation based tool-set. A custom scheduler is developed to provide a TCP/IP socket and shared memory interfaces to external simulators, and to control simulation. The communication model can consist of many modules simulating different layers of OSI (Open Systems Interconnection) Reference Model. Many such modules have been available from INET Framework [220] – an OMNeT++ extension. These modules, however, have to be modified to include the support for working with developed custom scheduler. For this purpose some further customization of INET modules relating to transport layer and data link layers is carried on. In the implementation, any module wishing to send/receive data to any external simulator needs to register itself with the custom

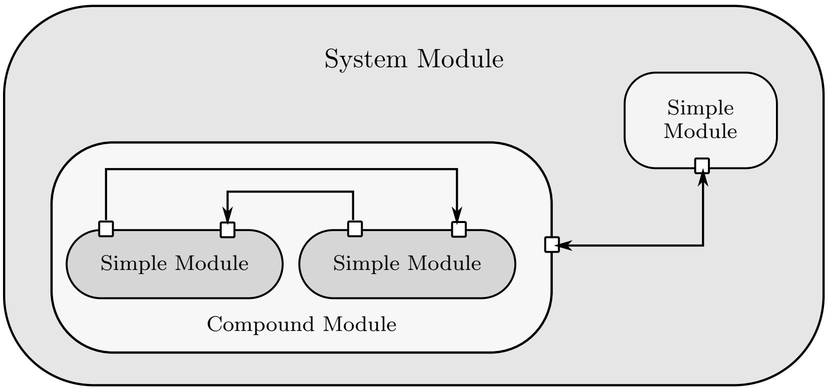


Figure 5.8: OMNeT++ supports an hierarchical structure. Two or more *Simple* modules can be combined to create a *Compound* module. Simple and Compound modules can be combined to form a *System* module. Both Simple and Compound modules have *gates* for exchanging *messages* but System module has none.

scheduler. The scheduler stores the received data, adds an event in the event queue and later delivers to the registered module. A schematic overview of the custom interface is shown 5.9.

5.6 Results

This section presents the results of co-simulation of communication infrastructure models together with power system model and control system model. For the comparisons, results are quantified using the specified KPIs and calculated during the co-simulation.

5.6.1 Reference Scenarios

The two reference scenarios – the Best Case and the Worst Case – simulated with ideal (infinite bandwidth and no latency) and worst communication (all communication links failed), respectively. These scenarios provide the best and worst performance of the system with respect to communication and are further used for comparison with the other scenarios. The Best Case scenario results are used to calculate the KPIs of all other scenarios including the Worst Case.

The Best Case Scenario

Figure 5.10 presents the power profile on the individual buses for the Best Case simulated with an ideal communication — an infinite bandwidth and negligible latency. As can be seen in the results, the coordinated controller is able to regulate the voltages on the secondary side according to the voltage measurement values from the network. The voltage limit violations can occur due to charging of electrical vehicles and the generated power of the photovoltiac systems. The control actions, through change of OLTC tap position timing, further indicates that the control action

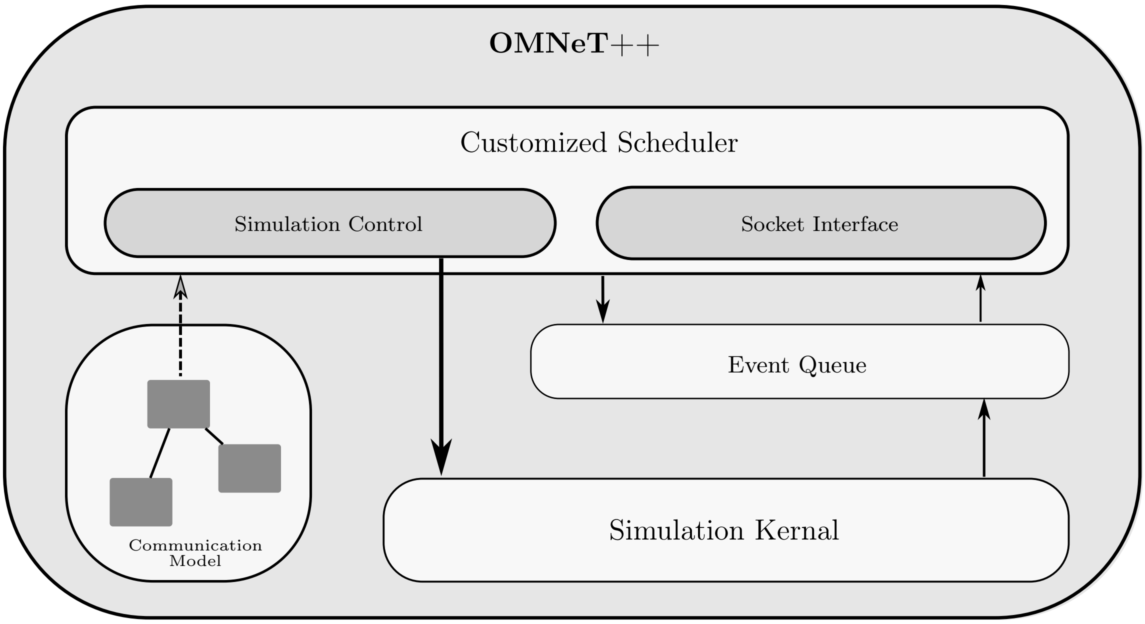


Figure 5.9: OMNeT++ coupling interface overview. A custom scheduler is developed to provide a TCP/IP socket and shared memory interfaces to external simulators. The communication model consists of many modules simulating different layers of OSI layers. Any module wishing to send/receive data to any external simulator registers itself with the scheduler. The received data is stored as an event in the event queue and delivered accordingly to the registered module.

happen immediately, whenever a voltage violation occur. The results further shows that even with the ideal communication there are some voltage limits violations at the Bus 1 and the Bus 3, mostly at the lower side. Since there is no communication delay, these violations can be due to the control algorithm.

The Worst Case Scenario

Figure 5.11 presents the results of simulating communication infrastructure with the Worst Case scenario. In this scenario, the communication with controller is no longer possible, hence the worst case. Figure 5.11a shows the voltage profile on the selected buses. As expected, there are lager voltage limits violations on Bus 1 and 3, due to electric vehicle charging and photovoltaic generations. Since the communication with controller is not possible, no control action through OLTC is carried out (Figure 5.11a) and the voltage violations prevails. An interesting point to note in Figure 5.11a is that there is no lower voltage limits violations. According to Figure 5.11b, total voltage limit violations crosses 300 minutes on the Bus 1 and 250 minutes on Bus 3.

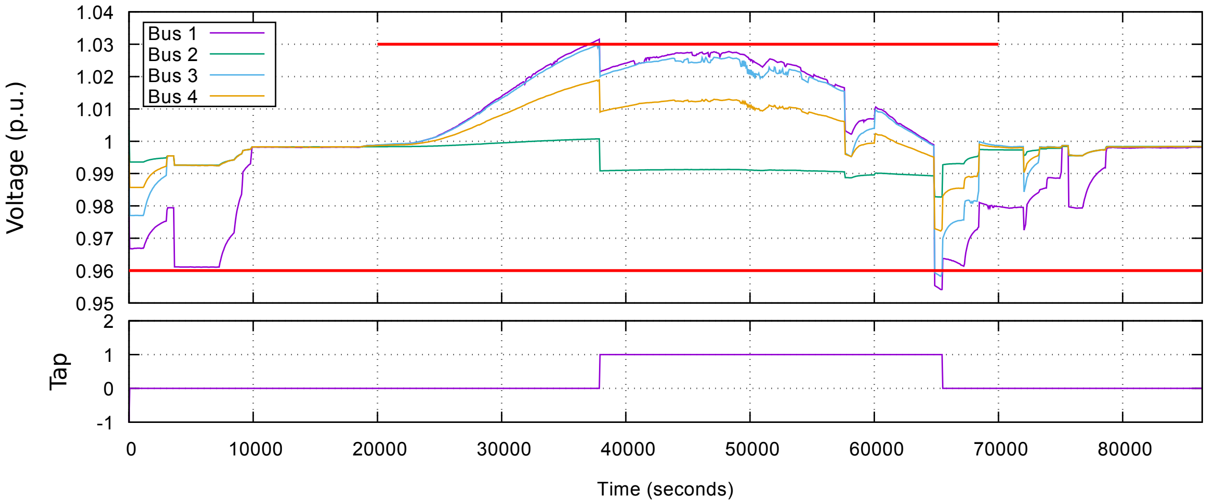


Figure 5.10: Results for the communication infrastructure model as the Best Case. The coordinated controller is able to regulate the voltages on the secondary side according to the voltage measurement values received from the network. The control actions are on time in setting the tap position of the OLTC whenever a voltage violation occurs.

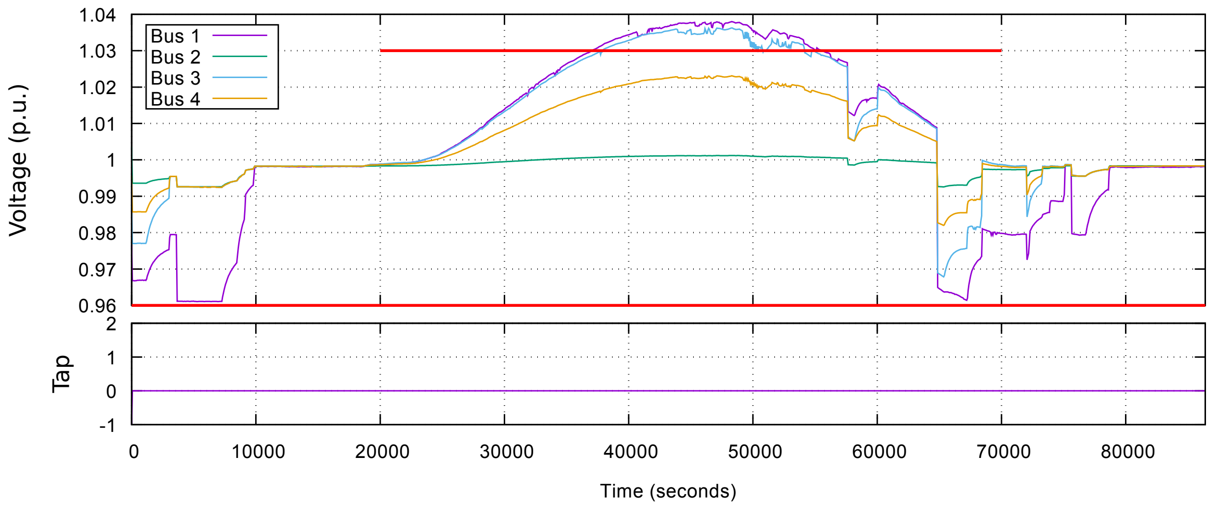
5.6.2 Communication Technologies

The communication infrastructure uses some communication technologies for achieving data communication tasks. There are many communication technologies that can be used for this purpose. These technologies can be broadly classified into three main categories – wired, wireless and Powerline communication. The results of co-simulating communication infrastructure models with different variation of these three communication technologies are presented in this section. Figure 5.12 presents the results of using wired communication with 1 *Gbps* bandwidth, Figure 5.13 presents the result for wireless technology model, while Figure 5.14, Figure 5.15 and Figure 5.16 show results of three variation of Powerline communication technology models.

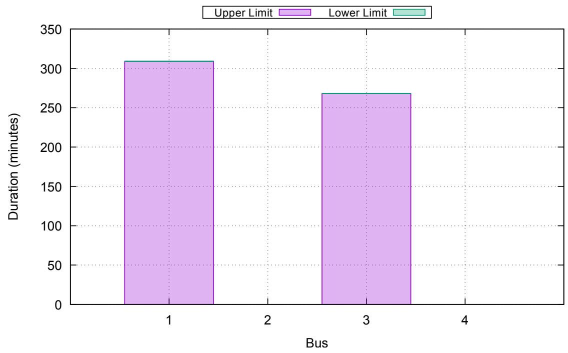
Wired Communication Technology

Wired communication technologies can provide a data rate of up to 100 *Gbps* over long distances and thus are among the fastest available. These technologies use copper or optical wires as communication medium and also considered very reliable. There are many examples of such communication technologies including telephone line, optical fiber networks, local area and wide area networks. These technologies are important for providing a high speed, real-time communication links and have many applications in Smart Grid domain.

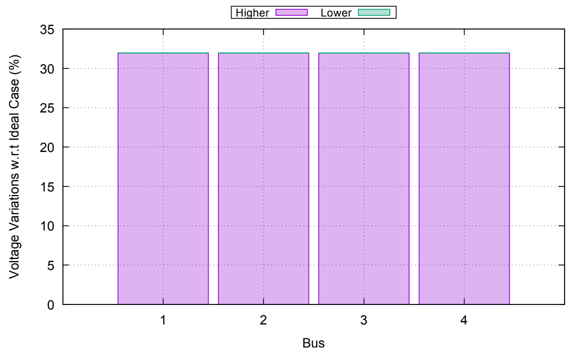
A model of communication infrastructure with a wired communication simulated along with the power and control system in the co-simulation environment is presented in Figure 5.13. The model of communication infrastructure comprises a start topology with Ethernet at link layer, TCP/IP



(a) Voltage profile over time of the selected buses in the system.



(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on selected buses.

Figure 5.11: Results of the Worst Case scenario when no communication is possible with controller hence no control action can be performed. As expected, a large voltage upper limit violations can be see on Bus 1 and 3. Similarly, there is more than 30 % deviations in voltage profiles with respect to the Best Case.

as network and transport protocols. The network in model has a bandwidth of 1 *Gbps*. The PVs are modeled as node of the network sending measurement and receiving the control actions.

From the Figure 5.12a, it can be seen that the control algorithm is able to regulate the voltage. There are some variations in the voltage profiles between this case and the Best Case as can be seen in Figure 5.12c. There is some over voltages for a duration of less than five minutes on the Bus 1 and the Bus 3 as in Figure 5.12b. The average communication delay is calculated to be 12 milliseconds and does not affect the performance of the controller (Figure 5.12d and 5.12e).

Wireless Communication Technology

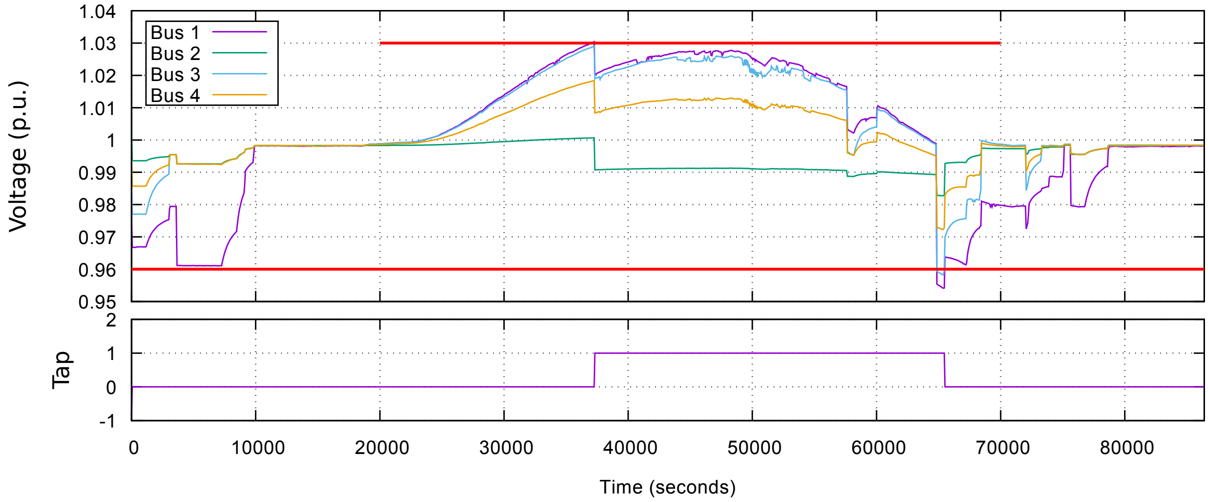
Wireless communication technologies are among the fast growing communication technologies today and use radio frequency as medium of communication. There are many variations of this technology including WiFi, WiMAX, 3G, GPRS, ZigBee, Bluetooth etc. Wireless communication technology is an import technology and is considered a strong candidate for Smart Grid deployments.

A mode of communication infrastructure with IEEE 802.11g is co-simulated with the proposed tool-set for the performance evaluation of the control algorithm and its effects on the underlying power system. In the model, PVs are modeled as wireless nodes that use wireless access points (APs) for sending network measurements and receiving control set points. The access points are connected to a backbone wired network through routers.

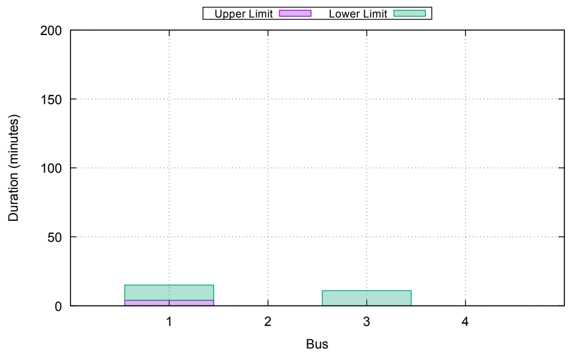
The results in Figure 5.13a, showing the voltage profile, indicates that the control algorithm is able to regulate the voltage. The resutls overall are similar to the Best Case, but there are some variations in the voltage profiles as can be seen in Figure 5.13c. The average communication delay is calculated to be 34 milliseconds and does not affect the performance of the controller (Figure 5.13d and 5.13e). Again, there are some over voltages for a duration of about 5 minutes on both the Bus 1 and the Bus 3 (Figure 5.13b).

Powerline Communication Technology

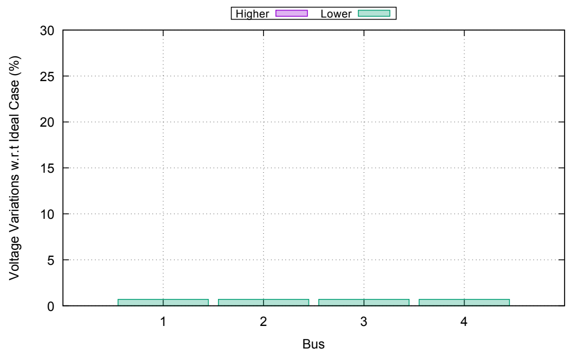
Powerline Communication (PLC) uses electrical power supply networks as communication medium and has a natural advantage over other communication technologies for Smart Grid applications. Even though it a harsh medium it is considered among the ideal candidates for implementing communication infrastructure for Smart Grid application. The design idea of PLC is the reduction of cost and in implementing communication infrastructure for new services. PLC can be used at all the three power system network layers – high voltage, medium voltage and low voltage. Efforts are going on for the standardization of the Powerline communication with regulations such as in Europe, CENELEC EN 50065 for communication in the frequency spectrum from 3 to 148 kHz. PLC can be broadly classified into Broadband and Narrowband PLC.



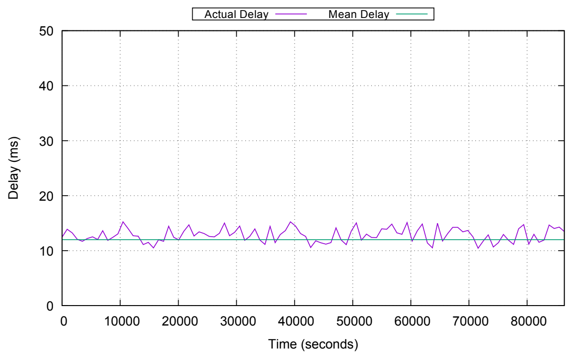
(a) Voltage profiles over time of all the buses in the system.



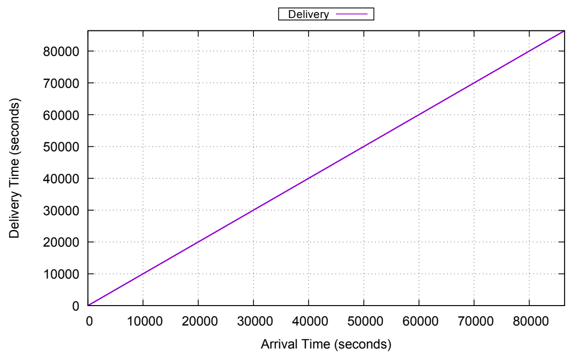
(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on selected buses.

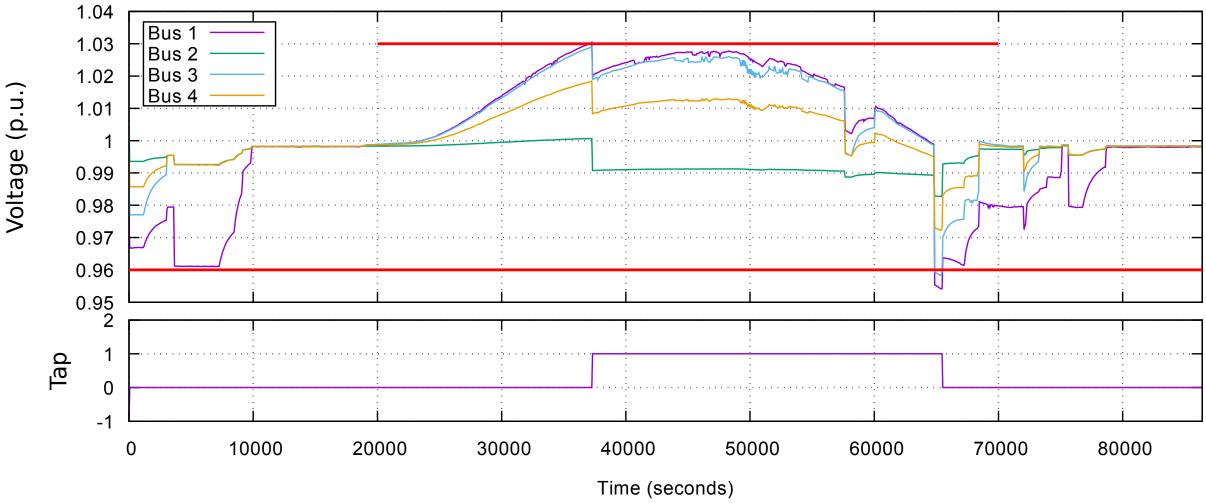


(d) Communication delay.

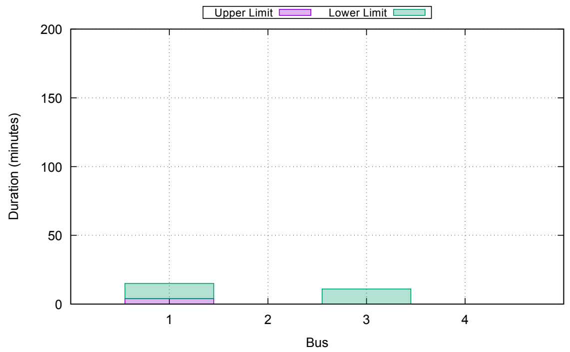


(e) Packet arrival and delivery time function.

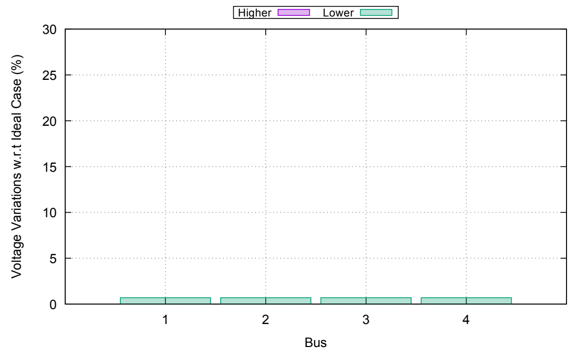
Figure 5.12: Results for communication infrastructure modeled with Wired 1 *Gbps*. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.



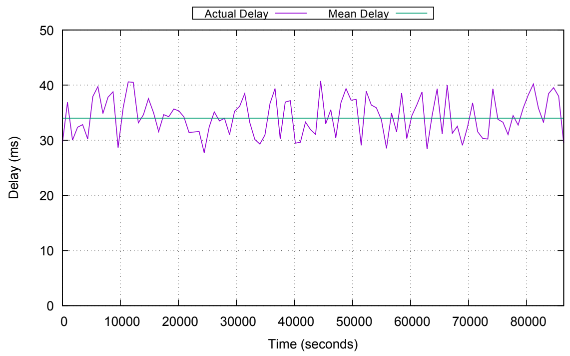
(a) Voltage profile over time of all the selected buses in the system.



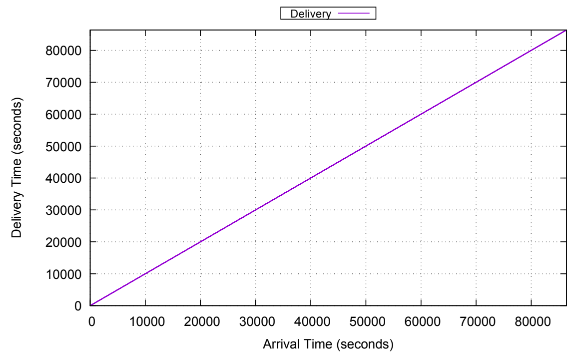
(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on selected buses.

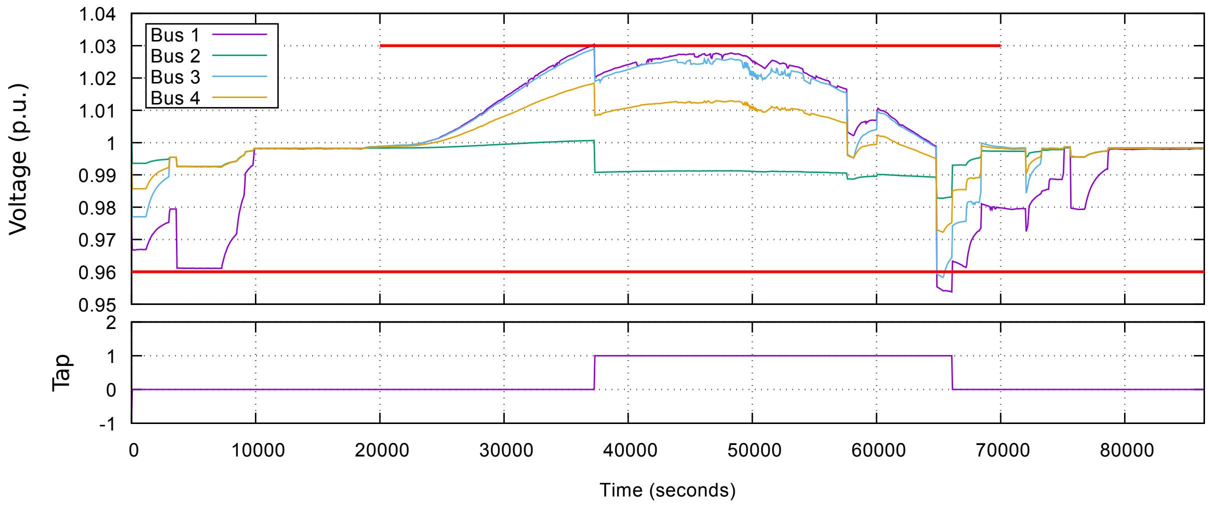


(d) Communication delay.

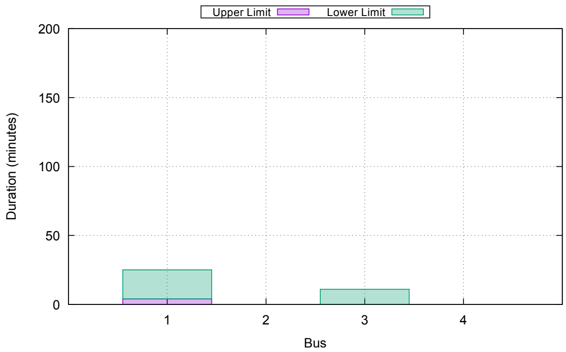


(e) Packet arrival and delivery time function.

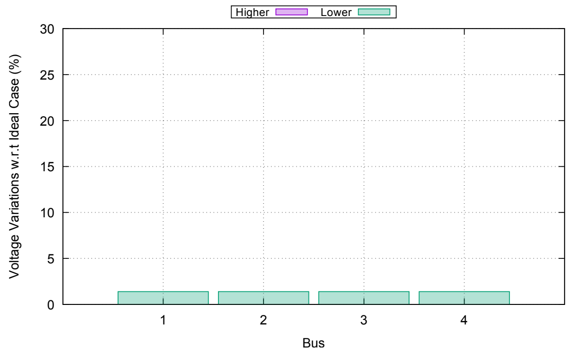
Figure 5.13: Results of co-simulation with communication infrastructure modeled as Wireless 54 *Mbps*. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.



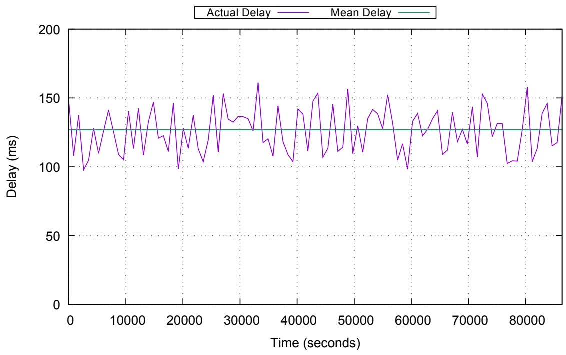
(a) Voltage profiles over time of the selected buses in the system.



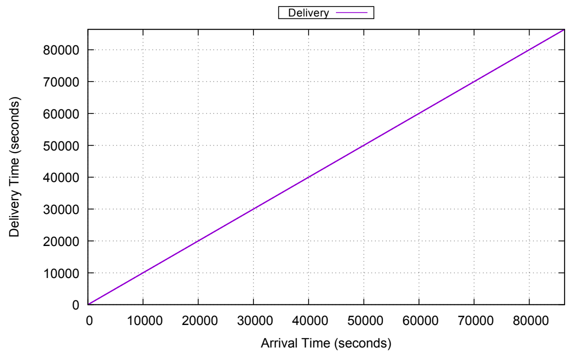
(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on the selected buses.



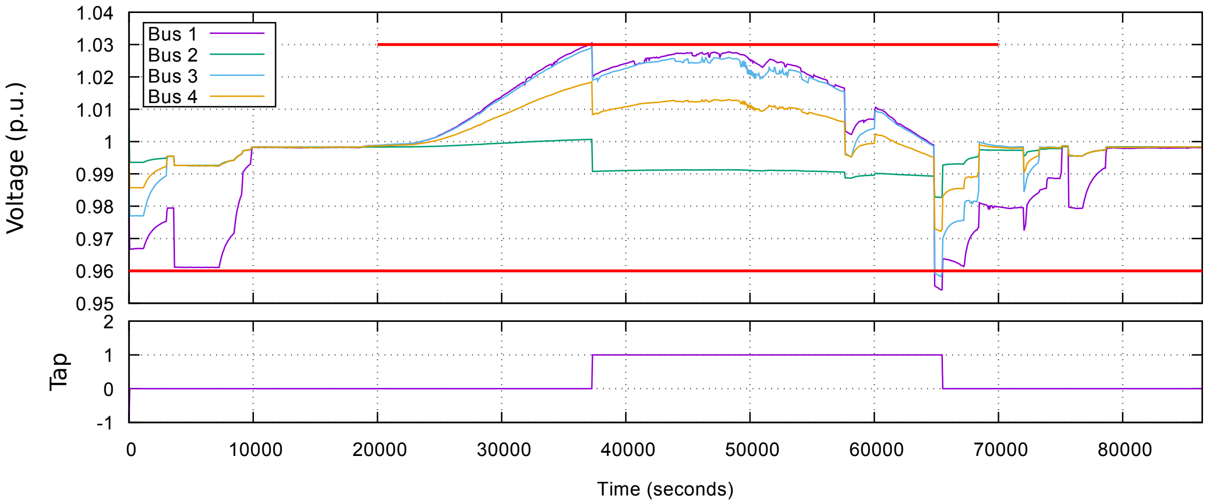
(d) Communication delay.



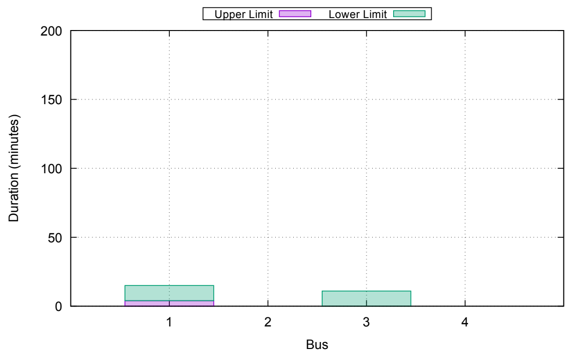
(e) Packet arrival and delivery time function.

Figure 5.14: Results of co-simulation with communication infrastructure modeled as PLC 1 *Mbps* Broadband Powerline communication. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.

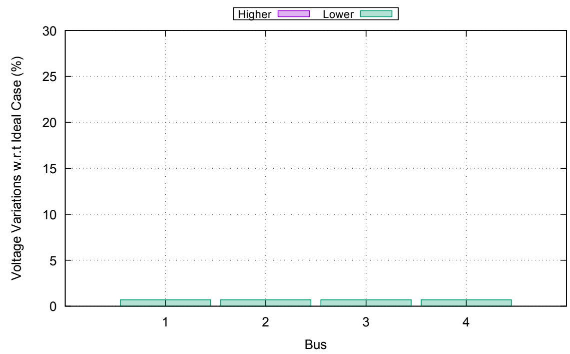
Considering the importance of PLC in Smart Grid, three variants of PLC are modeled for communication infrastructure. The first model used a Broadband PLC with 1 *Mbps* while the second and third communication infrastructure models represents the Narrowband PLC with 128 *kbps* and 33 *kbps* bandwidths. The results from the three scenarios are presented in Figures 5.14, 5.15 and 5.16, respectively.



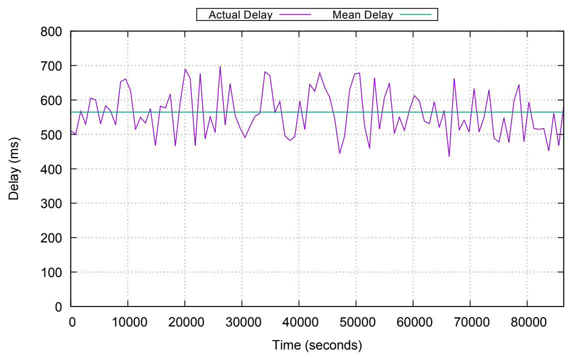
(a) Voltage profiles over time of the selected buses in the system.



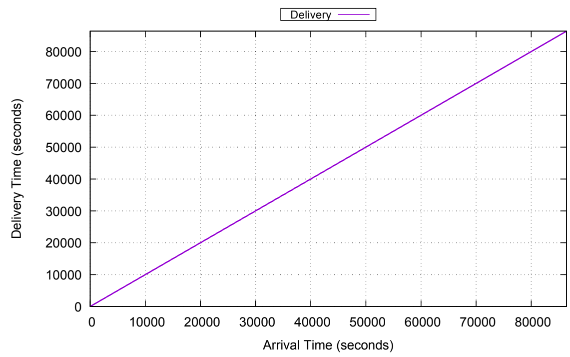
(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on selected buses.



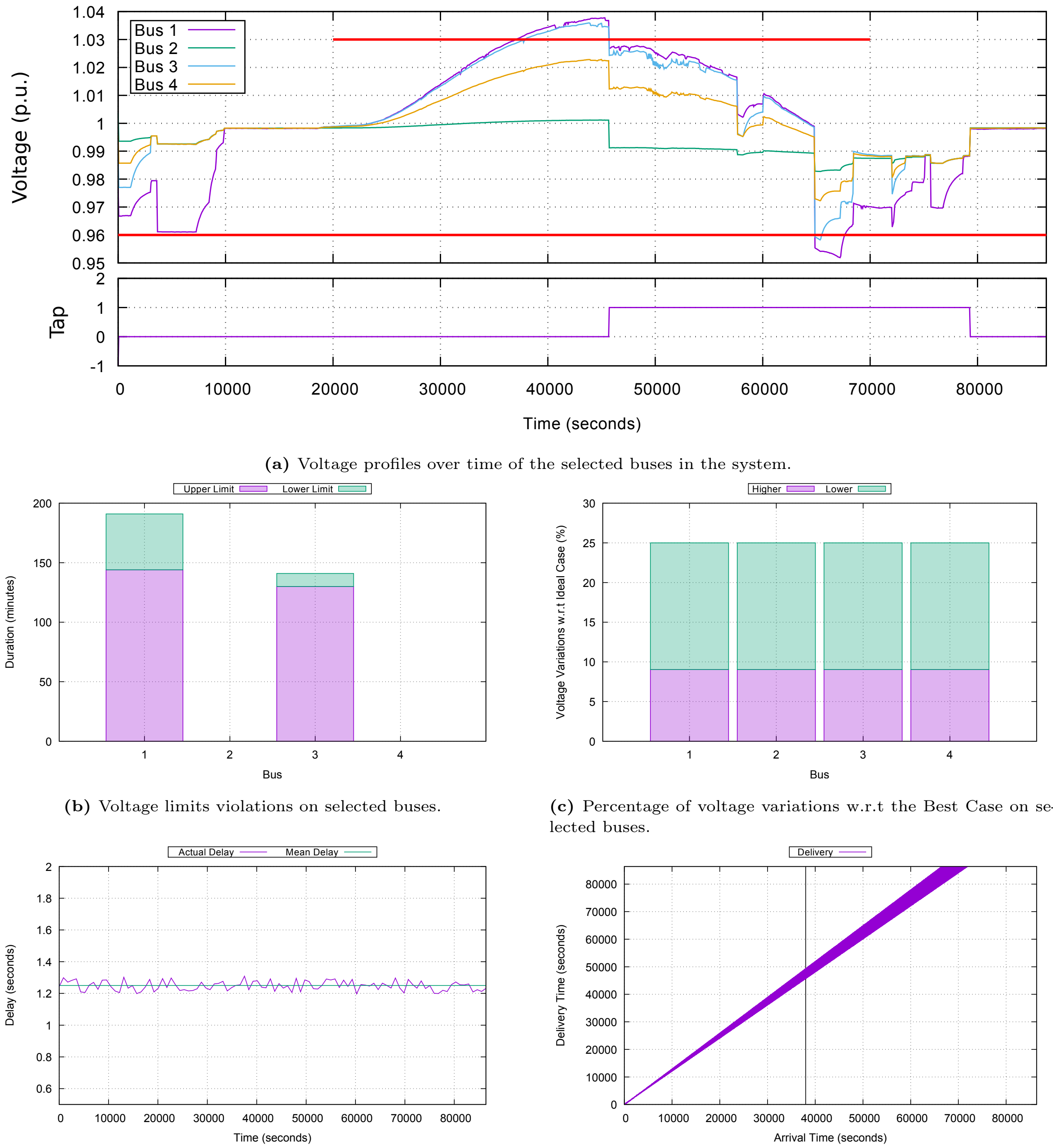
(d) Communication delay.



(e) Packet arrival and delivery time function.

Figure 5.15: Results of the co-simulation with PLC 128 *kbps* Narrowband PLC with 128 *kbps* communication infrastructure model. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.

Powerline is a harsh and slow medium. Since, the bandwidth for first two scenarios (PLC 1 *Mbps*



(a) Voltage profiles over time of the selected buses in the system.

(b) Voltage limits violations on selected buses.

(c) Percentage of voltage variations w.r.t the Best Case on selected buses.

(d) Communication delay.

(e) Packet arrival and delivery time function.

Figure 5.16: Results of co-simulation with communication infrastructure modeled as PLC 33 *kbps* Narrowband Powerline communication. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.

and PLC 128 *kbps*) are sufficient for traffic intensity, the control algorithm is able to regulated the voltage (Figure 5.14a and 5.15a). But in the case of third (PLC 33 *kbps*), the bandwidth is not sufficient and has caused a large communication delay, more than one second on average

(Figure 5.16d). This large delay in receiving measurements causes the control actions to lag behind.

5.6.3 Communication Failure

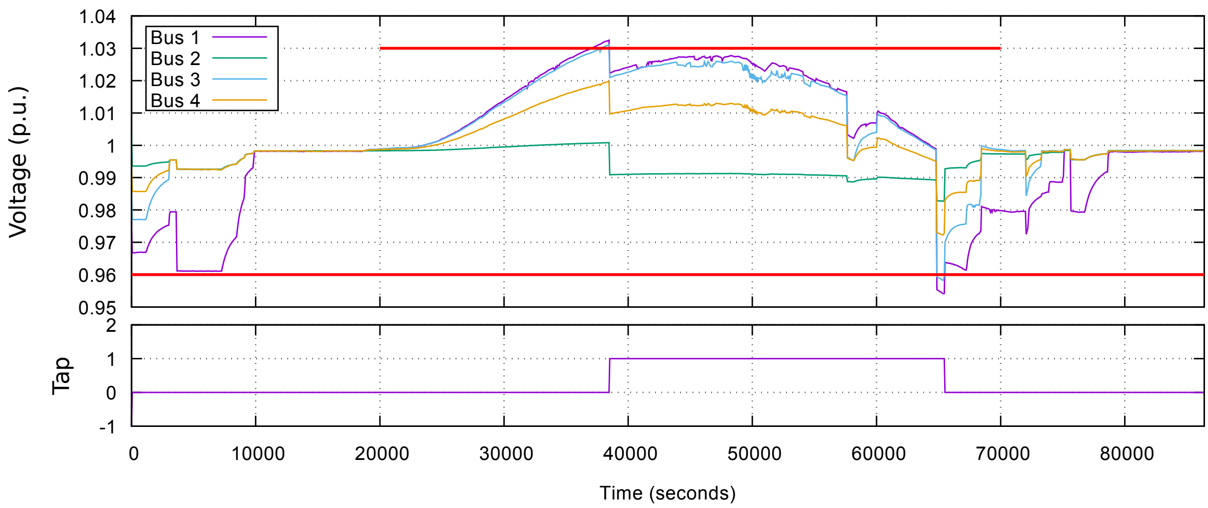
Communication failures due to intentional (cyber attacks etc.) or unintentional (natural disaster, faults etc.) reasons could result in lack of awareness for controllers and could lead, further, to failures in the power system. Some of these failures could be catastrophic and it is therefore, important to be able to access performance of the system in case of communication failures.

A communication infrastructure model when one of the network measurements units (VM2) is unable to communicate with the controller, is simulated and the results are presented in Figure 5.17. The underlying communication network is an Ethernet 1 *Gbps* with TCP and IP as transport protocols. As the results shows, the failure of one measuring unit did not affect the performance of the controller and it is able to regulated the voltage. Figure 5.17b indicates that there is a slight increase in the duration of over voltage on the bus where the failed unit is placed.

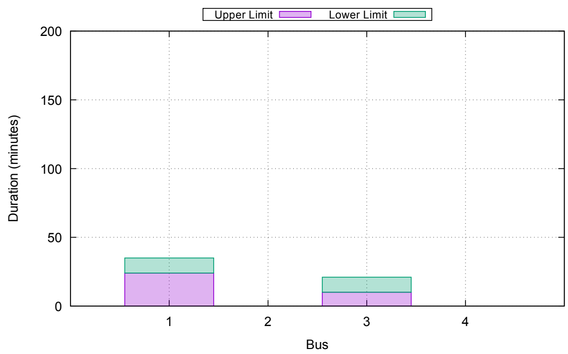
5.6.4 Communication Infrastructure Sharing

Many applications and services may be deployed using the same communication infrastructure in the future, as laying a dedicated network for every new service/application may not be a feasible option. It is therefore, helpful to measure the performance of the system under such conditions. A communication channel scenario is model with the base network having a wired communication technology with a bandwidth of 1 *Gbps* with Ethernet as the link layer, TCP and IP as network and transport protocols. A constant 10 *Mbps* SCADA traffic is modeled to be passing through the same network that is being used for sending network measurements and receiving control actions.

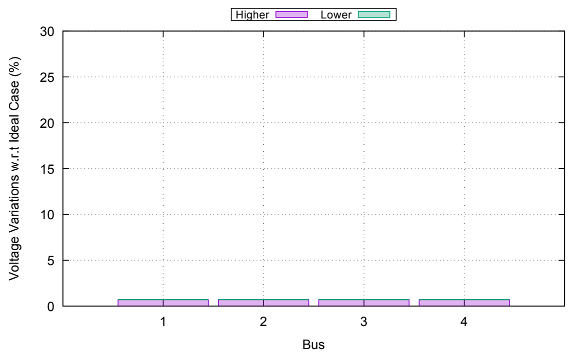
Figure 5.18 shows the results of co-simulation with this model. As the results indicate, the background traffic passing through the communication infrastructure has considerably overloaded the network, causing measurements and control actions to be delayed. Due to lag introduced by this delay, the control system is unable to regulate the voltage and there are large duration of over voltages (more than 300 minutes). In facts the results are more close to the Worst Case performance.



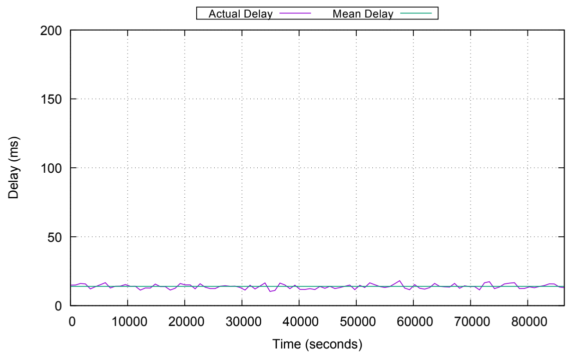
(a) Voltage profile over time of the selected buses in the system.



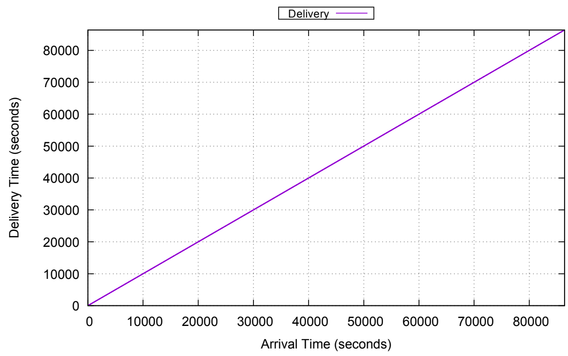
(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on selected buses.

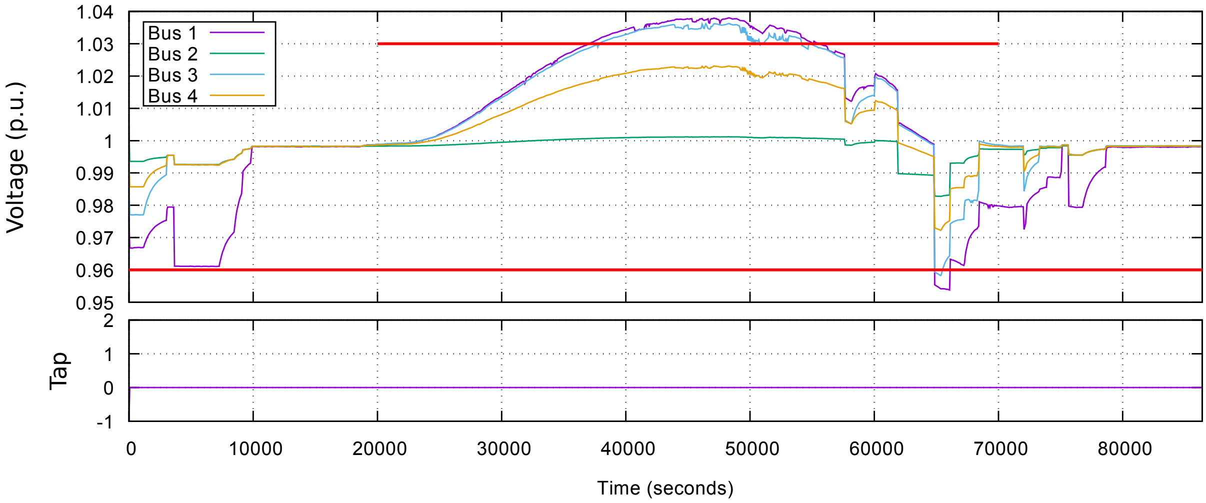


(d) Communication delay.

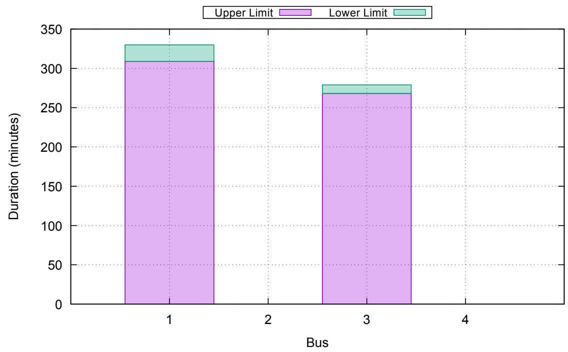


(e) Packet arrival and delivery time function.

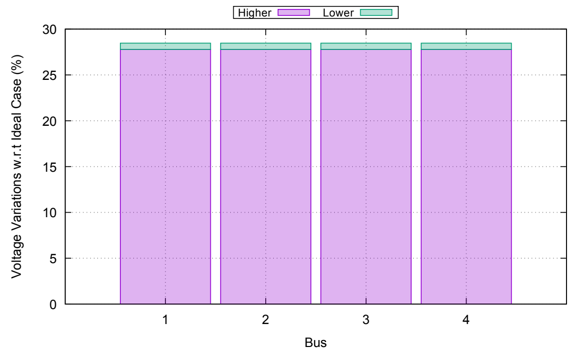
Figure 5.17: Results of co-simulation when in the communication infrastructure model, one of the measuring unit (VMU_2) fails to communicate with the controller. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.



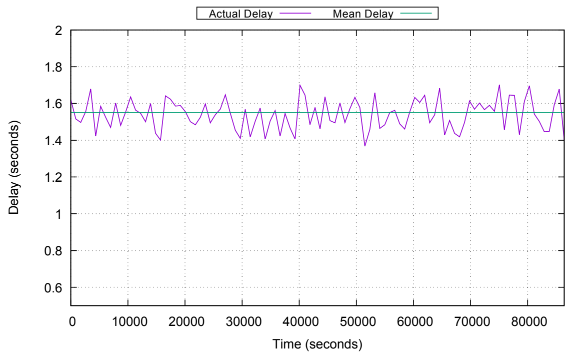
(a) Voltage profiles over time of selected buses in the system.



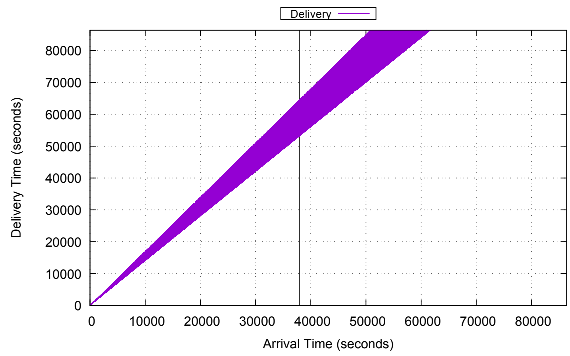
(b) Voltage limits violations on selected buses.



(c) Percentage of voltage variations w.r.t the Best Case on selected buses.



(d) Communication delay.



(e) Packet arrival and delivery time function.

Figure 5.18: The results of co-simulation when the communication infrastructure is modeled as having a 10 $Mbps$ constant background traffic over Wired 1 $Gbps$ network. The results are showing voltages profiles, losses and duration of the voltages violations. Average and actual communication delay values along with message arrival and delivery times.

5.7 Summary

This chapter has presented the first case study to show the effectiveness and applicability of the proposed tool-set. The presented case study is an innovative Smart Grid solution to the voltage regulation problem in a low voltage residential network with high penetration of photovoltiac systems and electrical vehicles. An IEC 61499 based controller, after receiving measurements from installed sensors in network, regulates voltage using an installed on load tap changing transformer (OLTC). Due to high dependence of control actions over communication infrastructure, this case study presents an analysis and quantification of performance, using KPIs, for varying communication infrastructure models and scenarios. The power system model of a 0.4 kV residential network is modeled with DIgSILENT PowerFactory, embedded controlled is implemented in 4DIAC-IDE and communication infrastructure models are developed with OMNeT++. For co-simulation, custom interfaces are developed for selected simulators (DIgSILENT PowerFactory, FORTE and OMNeT++) where TCP sockets are used for intra-simulator communication. Description of results, including calculated KPIs and voltage profiles are also presented.

6 Case Study II – Coordinated Voltage Regulation in Low Voltage Distribution Network Using Coordinated Active Power Curtailment

After the presentation of first case study in the previous chapter, this chapter presents the second case study, describing the communication infrastructure analysis for a Smart Grid solution with a coordinated voltage controller. The methodology described in Chapter 4, is applied and the co-simulation environment consists of power system dynamic simulator DIgSILENT PowerFactory, discrete event communication simulator OMNeT++ and coordinated controller implemented in Python. The simulators are coupled with custom interfaces to provide data exchange over TCP/IP sockets. Figure 6.1 highlights the identified requirements address in this case study (RMS power system simulation, centralized controller, real-time simulation control).

The problem addressed in this case study is of dealing with the unfairness when the active power curtailment scheme is used for regulating voltage in a low voltage distribution network with many Photovoltaic Systems (PVs). A coordinated secondly voltage controller is implemented to provide fairness. The controller uses a communication infrastructure for receiving measurements from PV inverters in the system and also for sending control actions. The dependency of controller over communication infrastructure makes communication infrastructure performance analysis necessary.

Subsequent sections present first the background and problem with the active power curtailment based voltage regulation schemes in Section 6.1, followed by the suitability and design in Section 6.2. Modeling of the power and control system along with key performance indicators of interest are described next in Section 6.3. Section 6.4 provides the reference and modeled scenarios, with respect to communication infrastructure. The conceptual details of the co-simulation, in addition to a description of coupling interfaces are discussed in Section 6.5. The results including calculated KPIs are presented and discussed in Section 6.6. The chapter concludes with a summary in Section 6.7.

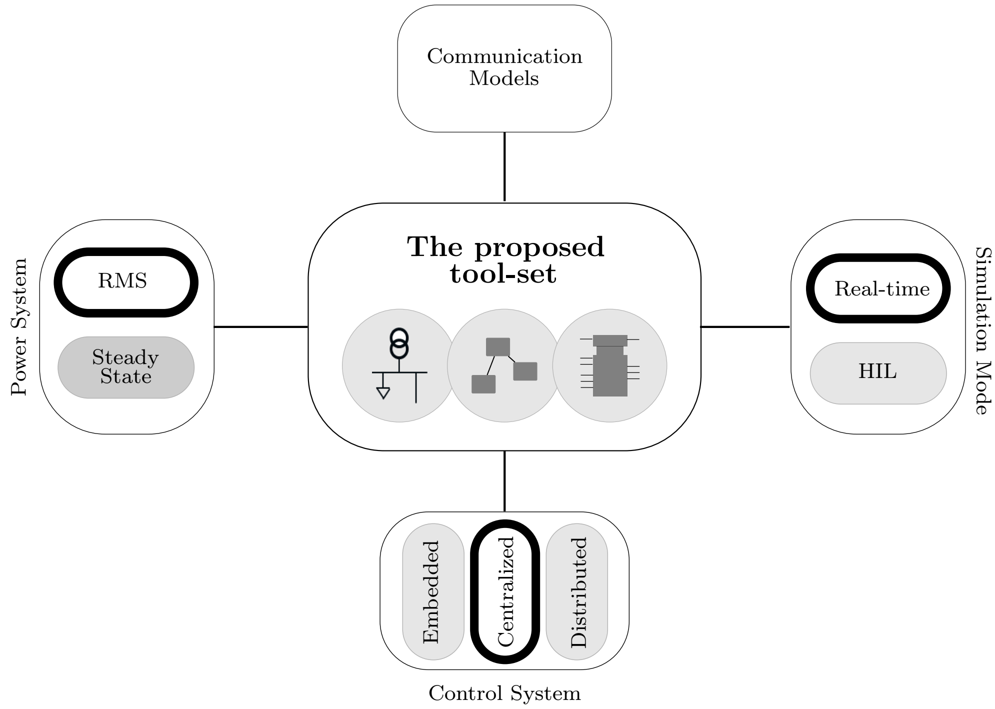


Figure 6.1: Parts of requirements addressed in co-simulation environment for this case study.

6.1 Background

Increased awareness of environmental concerns due to greenhouse gas emissions from traditional power generation methods have contributed significantly towards the efforts to find clean and green energy sources. Among the prominent objectives (see Section 2.2) of the Smart Grid vision are enabling the use of green energy resources such as the photovoltiac systems, wind and biomass etc. These power generation sources are considered clean and green having low greenhouse emission footprints as compared to traditional fossil fuel based power generation sources (see Figure 2.2). Furthermore, due to their relatively small size these resources can be distributed near loads and thus can reduce transmission losses.

Increased hosting of these intermittent, non-dispatchable and usually consumer owned (e.g. rooftop PVs) distributed generation resources at the low voltage distribution networks can cause power quality and reliability problems. As a crude solution, some utilities impose a limit on the number of such distributed generators that can be hosted without a detailed impact analysis. By imposing these limits, the utilities avoids the over voltage problem at the cost of discarded clean and green energy that is not allowed to be feed-in to the system. A more elegant solution other than conservatively limiting the number of renewable distributed generators is to use PV inverters with one of the active power curtailment schemes. This solution enables the distributed generations to inject their maximum available output as long as this does not create over-voltage situation and violates the power quality standards imposed in e.g. EN 50160. Whenever a voltage limit violation is detected, the active power of the distributed generator is curtailed. Although, the active power curtailment scheme look attractive but it has some inherent unfairness. It favors the distributed generator located near the feeder by low power curtailment when voltage limits are violated and curtails more power from the distributed generator locate farther. This unfairness could result in relatively more loss of revenue for distributed generator owners, located far from feeder than those near it [TL11, GRP16].

6.2 Suitability and Design

This case study is about introducing fairness in the use of active power curtailment schemes when applied in the PV inverters so that each distributed generator (in this case roof-top PVs) participate equally in voltage regulation. The modeled power system is a low voltage distribution network where customer-owned roof-top PV systems are injecting power. A coordinated remote secondary controller is implemented aiming at reducing the unfairness by equal participation of all distributed generator connected to the same feeder. The controller, after receiving measurements from installed PVs, calculates the safe maximum active power that can be allowed to be injected into the distribution network.

The dependency of control algorithm on communication infrastructure make is necessary to perform a detailed analysis of different communication scenarios. In this case study the communication scenarios are analyzed using the co-simulation of power system and control system. The modeled communication scenarios are divided into communication technology and commutation failure categories.

This case study is selected for the analysis of its centralized coordinated control system performance under varying communication infrastructure models and to quantify the effects. It will help in showing the effectiveness of proposed co-simulation based tool-set in analyzing RMS power system simulation, centralized controller, real-time simulation control (Figure 6.1) in a Smart Grid solution.

6.3 Modeling

Modeling is the first step in the analysis according to methodology (Figure 4.2). The power system and coordinated control are modeled and implemented with the DIgSILENT PowerFactory and Python respectively, while communication modeling is carried out in OMNeT++. Key Performance Indicators (KPIs) of interest are specified to be calculated for the quantification of results and comparison of scenarios.

6.3.1 Power System

The electrical power grid needs to be modeled for the use in the proposed co-simulation, where communication infrastructure models with varying parameters and scenarios are be investigated. The power system modeling is carried out by using the commercial simulator DIgSILENT PowerFactory [205]. The DIgSILENT PowerFactory is a sophisticated highly specialized, flexible and extendable platform for power system modeling and simulation. It provides a combination of both the graphical and scripting based methods for almost all the areas of power system including generation, transmission, distribution etc. Although a larger library of models exists in the tool but it is also possible to add new models using DIgSILENT Simulation Language (DSL). For dynamic simulation of power system, the tool provides many functionalities including load and power flow calculations, reliability and contingency analysis, RMS simulations and many more. The tool also supports application programming interfaces (APIs) that can be used to communicate with other simulators. It further supports the automation using DIgSILENT Programming Language (DPL) [FMGL15].

The power system chosen for this case study is a typical 0.4 kV rural low voltage residential network. The low voltage distribution network consists of 2 feeders (feeder 1 and 2). There are 27 customers and among them 16 have roof-top PV system injecting generated power into the network. These PV systems are having a varying generation capacities. Among the 16 PV system, nine are installed at feeder 2 while the remaining seven are on installed at feed 1. The secondary voltage control monitors the nine PV system installed at feeder 2. The model is depicted in Figure 6.2.

6.3.2 Control System

The coordinated secondary controller for introducing fairness in voltage control using the active power curtailment scheme is implemented in Python Programming Language [230]. The controller is connected to PV systems through communication infrastructure and receives the measurements. Based on these measurements, the algorithm calculates the curtailed power and send the maximum allowed injectable power to each PV inverter. The algorithm is divided into four main steps as depicted in Figure 6.3. In the first and second steps, feeder end sensitivities and voltage changes are calculated while in the third and fourth steps, the required active power reduction and critical voltages on each connected node are calculated.

6.3.3 Key Performance Indicators (KPIs)

KPIs are used to calculate application dependent and important quantities and are used to quantify and compare different scenarios. For this case study, the following KPI from power system are specified to be calculated for each simulation scenario.

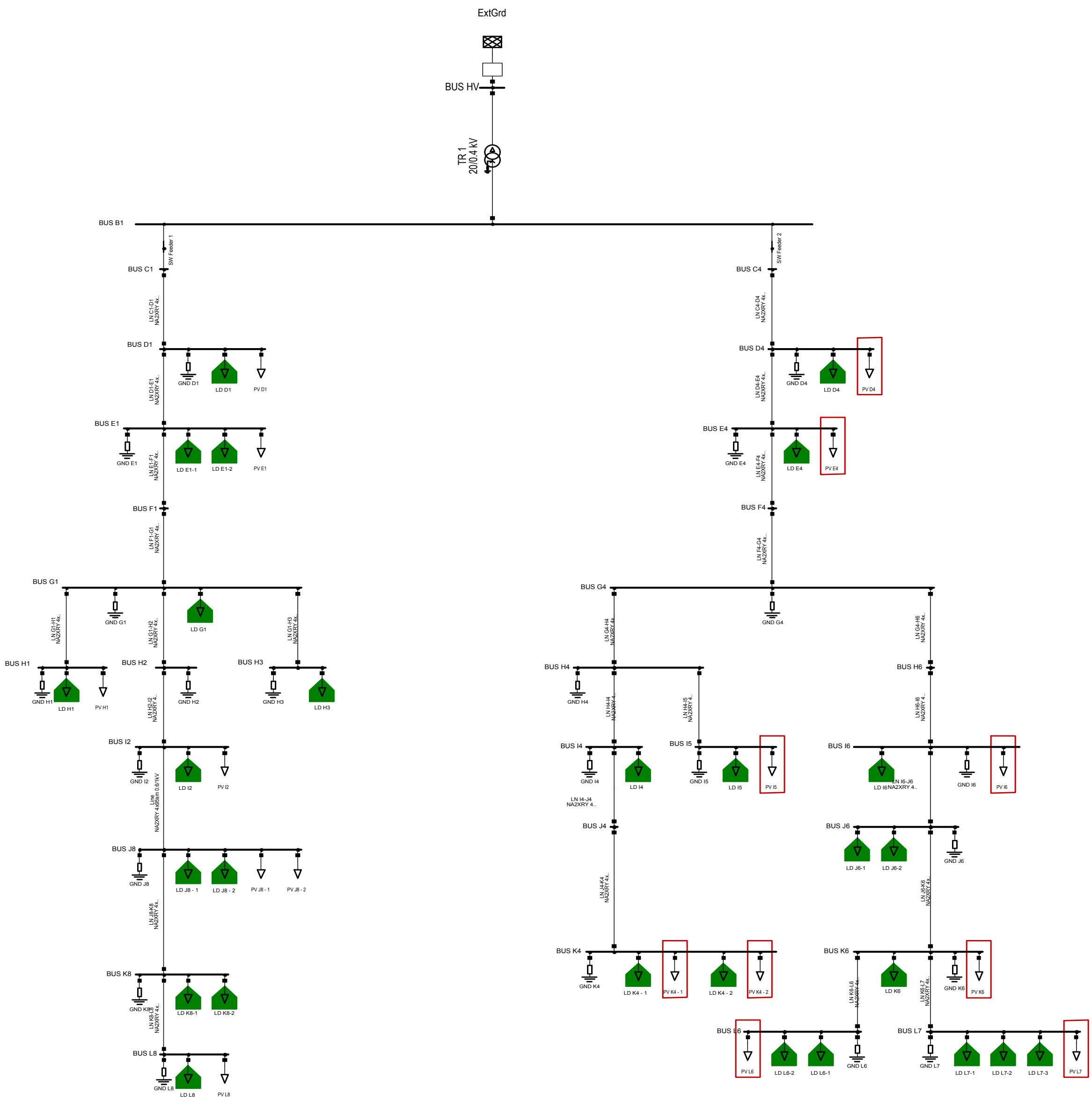


Figure 6.2: Power system model of a 0.4 kV rural low voltage residential network. The distribution network consists of 2 feeders (feeder 1 and 2) and has 27 household customers (marked with green houses and red boxes). Among them 16 have roof-top PV system injecting generated power into the network with varying generation capacities. Among these 16 PV systems, 9 are installed at feeder 2 while the remaining 7 are installed at feed 1. The secondly voltage controller monitors 9 PV system installed at feeder 2 (marked with red boxes).

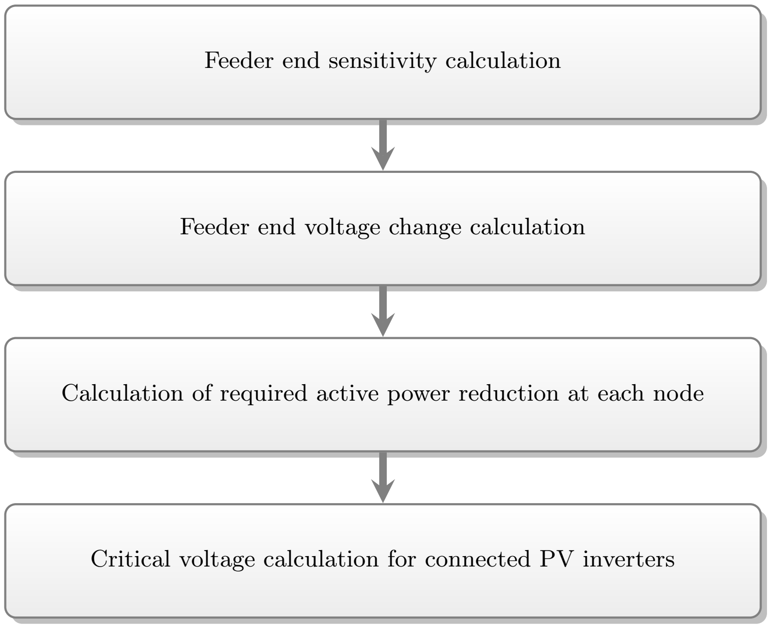


Figure 6.3: Major steps of active power curtailment based control algorithm, implemented in Python.

Voltage variation KPI is calculated as defined in Equation (5.1) and measures the voltage deviations on the selected buses with respect to the Best Case (with ideal communication). While Voltage Violation KPI is calculated using Equation (5.3) and sum the duration of voltage violations on selected buses. The third KPI calculates the losses due to curtailed power to avoid voltage problems. Equation 6.1 [LGP16] is used for the calculation of this KPI.

$$Total\ Curtailed\ Energy = \sum_{i=1}^{n} E_i^{cur} \tag{6.1}$$

$$E_i^{cur} = \int P_i^{cur},\ for\ i = 1, \ldots, n \tag{6.2}$$

$$P_i^{cur} = P_i^{inv} - P_i^{mppt} \tag{6.3}$$

Where:

n: number of installed photovoltiac systems,
E_i^{cur}: actual active power output,
P_i^{mppt}: maximum active power output,
E_i^{cur}: curtailed power.

Although, only two KPIs are specified for this case study but the methodology is capable of calculation any number of specified KPIs of interest.

Similarly, for communication system, the chosen KPI is the communication delay. This KPI is significant as it is one of the important measure that could affect the control action. The control action is dependent on the voltage measurements from the network and if the measurements are delayed, control actions will also lag behind. The KPI is calculated in accordance with Equation (5.4) and includes service time, propagation delay at the physical channel and queue time.

6.4 Communication Scenarios

The communication infrastructure needs to be modeled in order to evaluate the performance of the control system and its effects on the underlying power. Different communication infrastructure models with varying parameters of three different communication technologies in addition to communication failures are modeled with OMNeT++ to be co-simulated with the power system and control system models.

The communication scenarios are categorized as reference and modeled scenarios. The reference scenario are used to measure the best and worst performances of the control system and underlying power system effects and are used to calculate the KPIs.

6.4.1 Reference Scenarios

For the reference, the Best Case and the Worst Case scenarios are modeled with communication infrastructure being the ideal for communication – with infinite bandwidth and negligible latency – and worst – no more communication possible – to be simulated together with power and control system models. These scenarios provide the best and the worst performance of the control system and helps is investigating its effects on underlying power system. The Best Case scenario results are later used to calculate the KPIs for other communication infrastructure models including the Worst Case.

The Best Case

This reference scenario represents the communication infrastructure having ideal communication characteristics. It helps in measuring the performance of the control system and its effects on the underlying system when there is no longer any communication dependency that could affect the performance of the system. The results from this scenario represents the best achievable performance with the supplied power system and control models and used latter to calculate some KPIs for the rest of the scenarios.

The Worst Case

In contrast to the Best Case, this reference scenario provides the worst possible performance with a communication infrastructure dependency. The communication infrastructure in this case do not allow any communication to take place between the PV inverters and controller. This scenario is useful to see how bad the control system behaves and what effects it can produce on the underlying power system when power system is no longer able to communicate with control system due to problems in communication infrastructure.

6.4.2 Modeled Communication Scenarios

Table 6.1 list various communication infrastructure model and scenarios specified for the investigation of the control and power system performance for this case study, categorized as technology and failures. In the first category, scenarios contains all major wired, wireless and Powerline communication technologies, while in second category two communication failure scenarios are specified.

Table 6.1: Communication Scenarios

Category	**Name**	**Description**	**Model**
Technology	Wired	Two variations of wired communication technology with 40 and 1 *Gbps* bandwidths, a star topology and TCP/IP over Ethernet.	Figure A.7
	Wireless	An infrastructure wireless communication technology (IEEE 802.11g) where Access Points are connected with a wired communication technology having 1Gbps bandwidth.	Figure A.8
	PLC	Three variations of Powerline communication with 1 *Mbps*, 128 *kbps* and 33 *kbps* bandwidths (IEEE 1901.1)	Figure A.9
Failures	Link Failure	Communication link between the nearest and the farthest PVs experience link failures, making it no longer possible to send measurements or receive commands.	Figure A.10 and Figure A.11

6.5 Co-simulation

This section describes the concepts, tools, coupling interfaces and setup of the co-simulation environment implemented to investigate the performance of the control and power system with varying models of communication infrastructure.

6.5.1 Concept

The conceptual view of the co-simulation setup is shown in Figure 6.4. The Smart Grid application is divided into three sub-systems; the power, communication and the control system. Three different simulators are used to simulate each of these sub-systems. The simulators are running independently without any master, in real-time synchronized with system clock. During the simulation, power system simulator (DIgSILENT PowerFactory) simulates the power system model (Figure 5.2) and send the voltage measurements using communication model descried in Section 5.4 and simulated with OMNeT++, to the control model implemented in Python. The control algorithm calculates the amount of active power to be curtailed, based on the measurements received from the network. The calculated set points are then sent to PV inverters for setting their maximum output so that the voltage could be regulated.

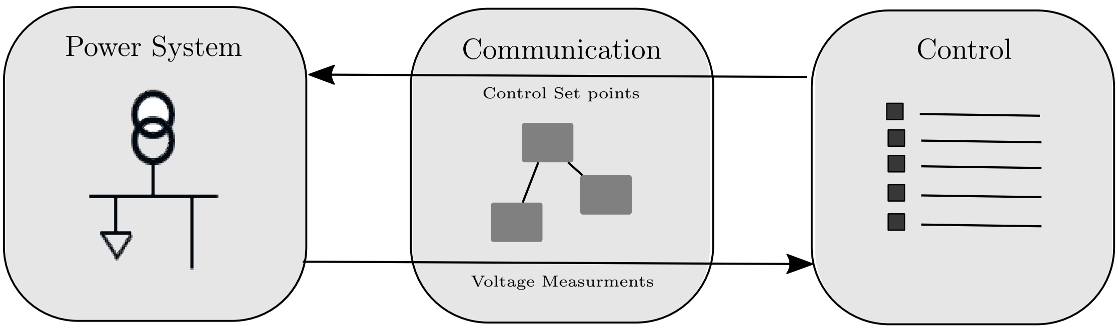


Figure 6.4: Conceptual overview of co-simulation. Voltage measurements are sent over communication infrastructure to control system while control set points are sent again using communication infrastructure to power system. The three participating simulators are running independently in real-time synchronized with system clock.

6.5.2 Simulator Coupling and Interfaces

Figure 6.5 shows simulation setup. Three simulators are used in the co-simulation environment; DIgSILENT PowerFactory for power system dynamic simulation, OMNeT++ for simulation of communication infrastructure and Python for control algorithm. In order for these tools to be able to exchange data (measurements and control set points), they need to communicate with each other during the simulation. Due to nonavailability of native coupling interfaces, custom individual interfaces implementing a common, well known and widely support protocol needs to be developed. In the implemented interfaces, the chosen protocol is the TCP sockets, that are both widely supported and well know. The details of the implemented interfaces along with a brief introduction to the tools are presented below.

DIgSILENT PowerFactory

The DIgSILENT PowerFactory is a sophisticated highly specialized, flexible and extendable platform for power system modeling and simulation. It provides a combination of both the graphical and scripting based methods for almost all the areas of power system including generation, transmission, distribution etc. Although a larger library of models exists in the tool but it is also possible to add new models using DIgSILENT Simulation Language (DSL). For dynamic simulation of power system, the tool provides many functionalities including load and power flow calculations, reliability and contingency analysis, RMS simulations and many more. The tool also supports application programming interfaces (APIs) that can be used to communicate with other simulators. It further supports the automation using DIgSILENT Programming Language (DPL) [FMGL15].

The interface used for coupling DIgSILENT PowerFactory is described in Section 5.5.2 and its schematic overview is shown in the Figure 5.5.

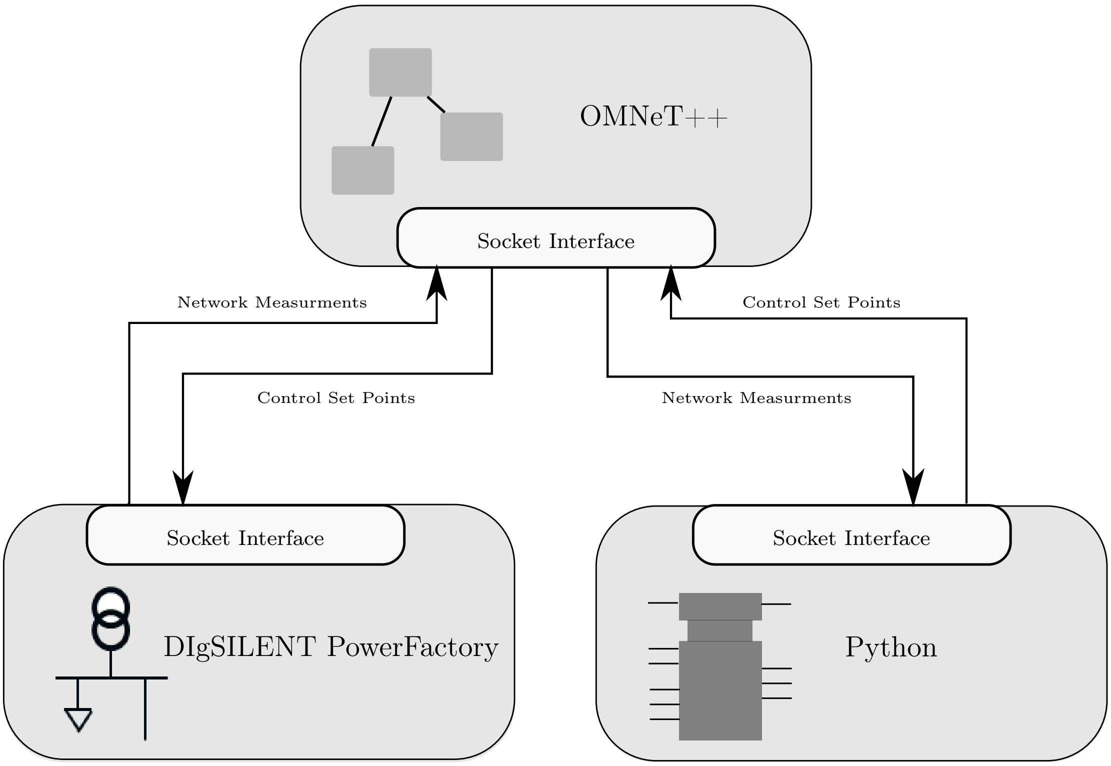


Figure 6.5: Co-simulation implementation and setup. Three simulator (DIgSILENT PowerFactory, OMNeT++ and Python) are used to simulate power, communication and control systems. Each simulator exposes an interface, custom built for simulator coupling and data exchange. During the power system dynamic simulation, network measurements from nine PVs are sent through communication simulator to control simulator. The control simulator calculates the new set points for individual PV inverters for the purpose of voltage regulation using the active power curtailment scheme. The communication system simulator pass the data to power system simulator where the received set points are applied.

Python

Python [230] is a cross-platform, powerful, object-oriented interpreted language with clean, simple and compact syntax. It has gained a lot of attention owing to its flat learning curve and its modular nature. It has a wide library of modules for different purposes; some notables modules are the module for numerical computing (`numPy`), scientific computing (`scipy`), symbolic computing (`sympy`), plotting (`matplotlib`) etc.

Twisted [235] is a networking engine written in Python for developing event-driven, cross-platform networking applications. It supports both a low-level and high-level set of tools and provides the support for many common transport and application layer protocols including TCP, UDP, HTTP, FTP etc.

The control algorithm is implemented in Python while the interface between Python and other simulators for the purpose of co-simulation is developed in Twisted networking engine. Using Twisted, a TCP socket interface is setup and later used for connection with other simulators (OMNeT++ in this case).

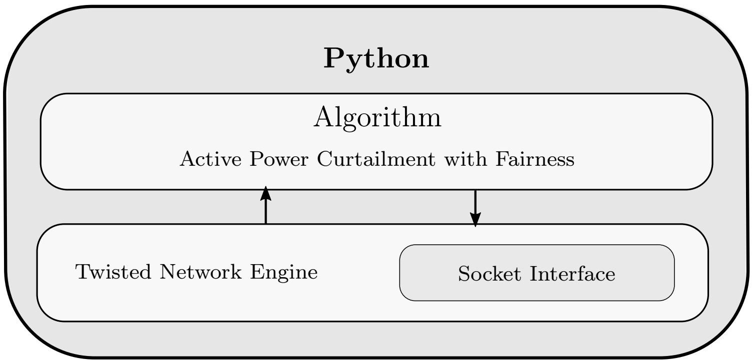


Figure 6.6: The coordinated controller and interface implemented with Python.

OMNeT++

OMNeT++ is used as the communication system simulator in the co-simulation setup. A custom scheduler is developed to provide a TCP/IP socket and shared memory interfaces to external simulators. The communication model consists of many modules simulating different layers of OSI layers. Any module wishing to send/receive data to any external simulator registers itself with the scheduler. The received data is stored as an event in the event queue and delivered accordingly to the registered module. A schematic overview of the custom interface is shown in Figure 5.9.

6.6 Results

This section presents the results of co-simulation of communication infrastructure models together with the power and the control system models using the co-simulation environment described in the previous section (Section 6.5). For the comparisons, the results are quantified using the specified KPIs and calculated during the co-simulation.

6.6.1 Reference Scenarios

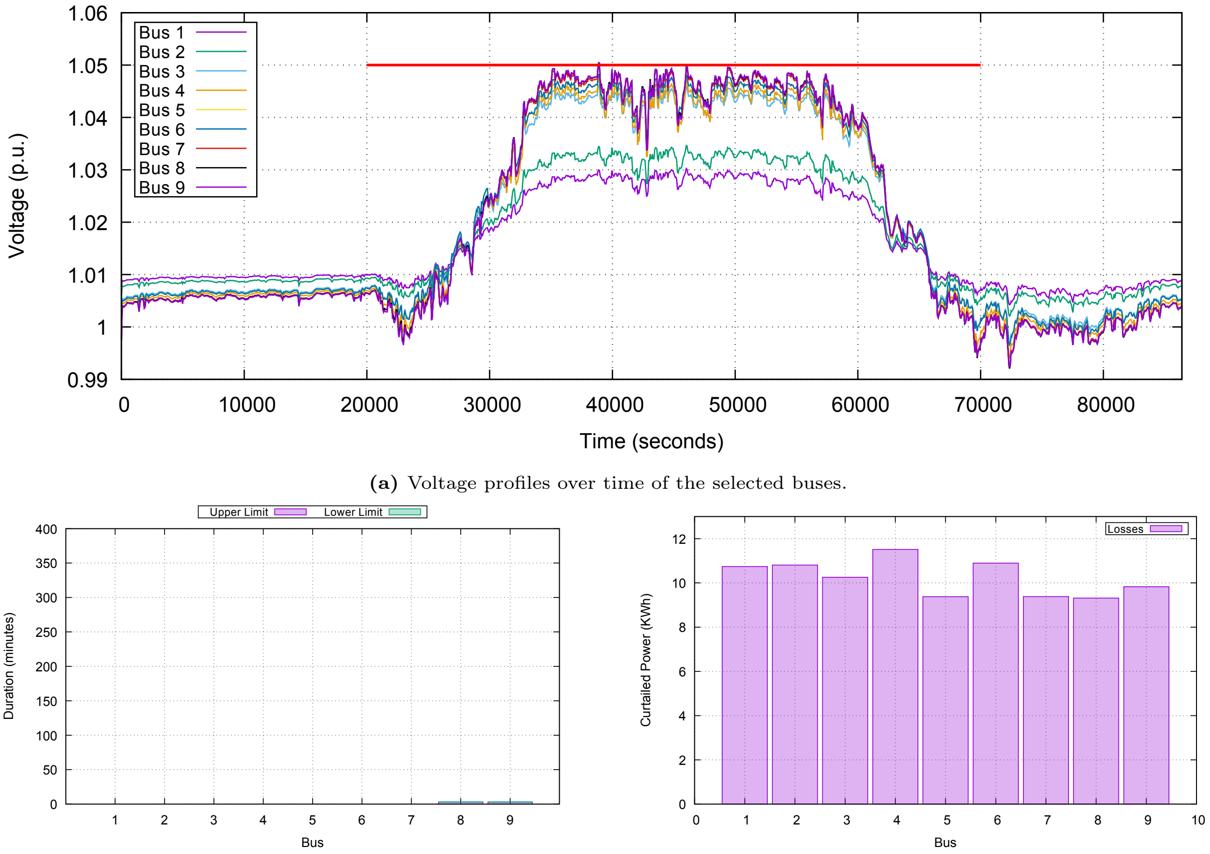
To provide the basis for comparison of the best and the worst performances depending on the communication infrastructure, two reference scenarios are simulated with the Best Case and the Worst Case communication infrastructure models. The Best Case models the communication infrastructure with infinite bandwidth and negligible delay making it extremely fast, while in the Worst Case, the communication infrastructure no longer allows any communication. The Best Case scenario results are later used to calculate the KPIs for other communication infrastructure models including the Worst Case.

The Best Case

Figure 6.7 presents results of reference scenario the Best Case where communication infrastructure is modeled with ideal communication channel having infinite bandwidth and negligible delay. As Figure 6.7a shows, the coordinated controller is able to maintain the voltage under limits on the selected buses. Figure 6.7c shows that there is, on average 11 kWh power curtailment on each PV by the controller to keep the system from going into over voltages state. Since, the voltage profiles are for a sunny day, the power curtailment starts at mid-day when PV generation is at peak. Figure 6.7b shows that there is a 3 minutes long upper voltage limits violation at both the Bus 8 and the Bus 9.

The Worst Case

Figure 6.8 shows the results for the second special reference case that is simulated assuming that the communication with controller is no longer possible. This case helps to measure the worst performance of the system when there is no control action possible. It further provides a reference for communication scenarios to gauge their performances. Figure 6.8a, as expected, shows the over voltages on all the buses. Similarly, as shown in Figure 6.8d, the duration of over voltages on the selected buses (except the bus 1 & 2) accumulates to 350 minutes. Since, there is no control action as the communication with controller is no longer possible, the curtailed power for PVs is almost zero. Furthermore, a larger voltage variations with respect to the Best Case is also visible in Figure 6.8e.



(a) Voltage profiles over time of the selected buses.

(b) Voltage limits violations on the selected buses.

(c) Resulting curtailed power on the selected PVs.

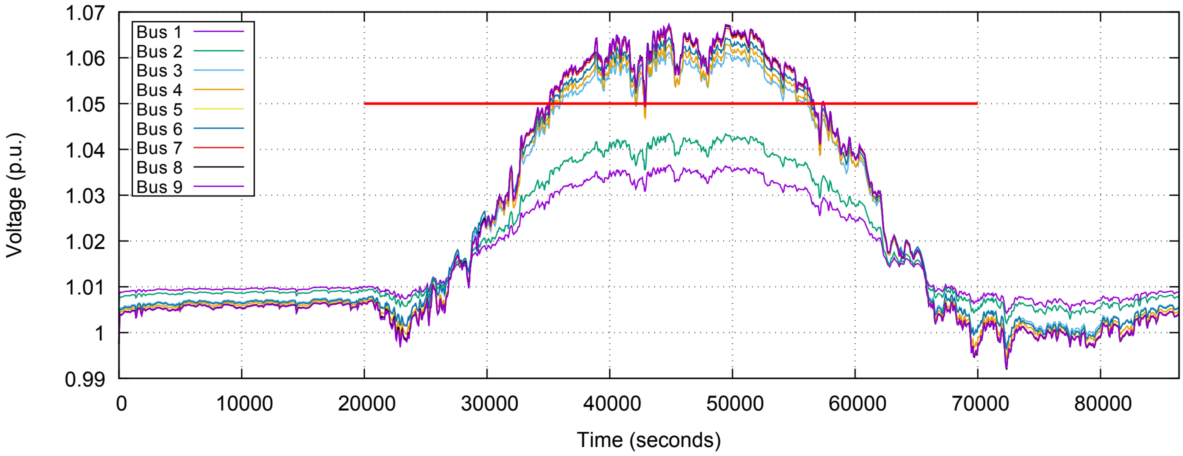
Figure 6.7: Results for co-simulation when the communication infrastructure is modeled as the Best Case. The results are showing voltages profiles, accumulated curtailed power and voltages violations.

6.6.2 Communication Technologies

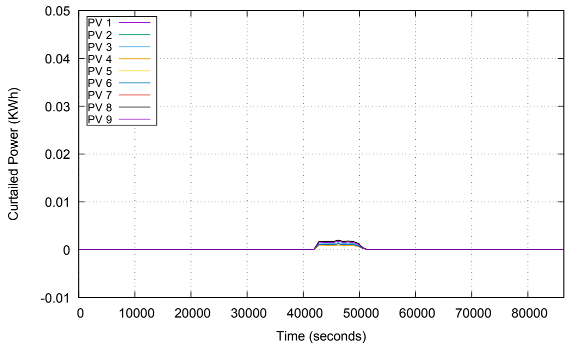
This section describes the results obtained from co-simulation when communication infrastructure is modeled with different variation of three (wired, wireless and Powerline communication) popular communication technologies. First result shown in Figure 6.9 is for Wired 1 *Gbps* communication infrastructure model, Figure 6.10 shows the result for Wireless 54 *Mbps* communication infrastructure model, the next three results corresponds to three variation of Powerline communication technologies and are shown in Figure 6.11, Figure 6.12 and Figure 6.13.

Wired Communication Technology

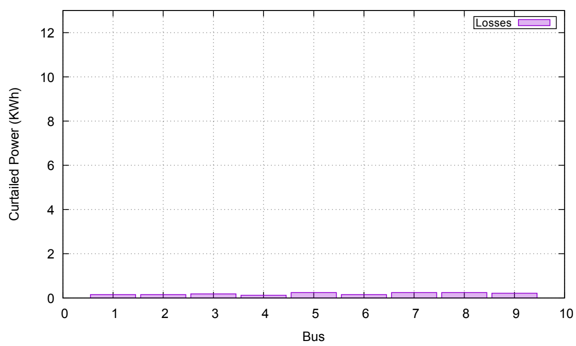
Wired communication technologies are among the fastest available communication infrastructure technologies, supporting terabit of data rates. These technologies are important for providing a high speed, real-time communication links and have many applications in Smart Grid.



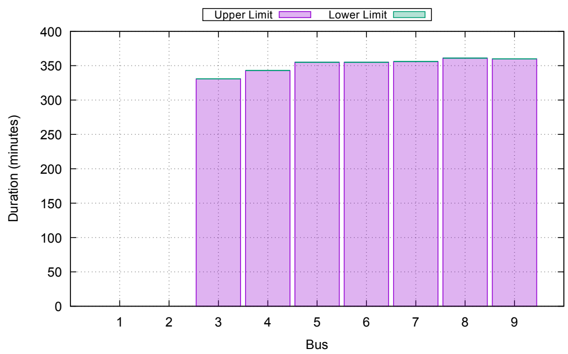
(a) Voltage profiles over time of the selected buses in the system.



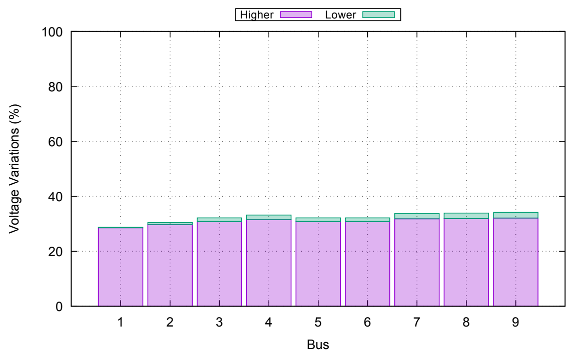
(b) Losses due to active power curtailment over time on the selected buses.



(c) Resulting curtailed power on the selected PVs.



(d) Voltage limits violations on the selected buses.



(e) Percentage of voltage variations w.r.t the Best Case on the selected buses.

Figure 6.8: Results for co-simulation when communication infrastructure is modeled as the Worst Case. The results are showing voltages profiles, accumulated and overtime curtailed power, voltages violations and voltage variations.

As part of analysis, two variations of wired communication technology are modeled and co-simulated. Figure 6.9 presents the results of communication infrastructure modeled as Wired 1 *Gbps*. The presented results include calculated KPIs and voltage profiles of the selected buses from the power system model. The results, overall, are near to Best Case performance, indicating that modeled communication infrastructure is suitable for this application. As the voltage profile in Figure 6.9a shows, the voltage on all the selected buses remains under limits, due to low average delay (100 ms) during transmission of network measurements and control set points as shown in Figure 6.9c. But, as Figure 6.9b shows, this timely control action has caused a large power to be curtailed from PVs (upto 11 kWh). There are only negligible voltage limits violations (Figure 6.9d) overall but a small variation (Figure 6.9e), in voltage profile can be seen, with respect to Best Case.

Wireless Communication Technology

Wireless communication technology is an import technology and is considered to be a candidate for Smart Grid deployment due to its relatively low infrastructure requirements. A variation of wireless communication technology is modeled to be analyzed through proposed tool-set. The result for this co-simulation with a communication infrastructure model of Wireless 54 $Mbps$ (IEEE 802.11g) are shows in Figure 6.10, presenting calculated KPIs and voltage profiles of the selected buses. The results, overall, are near to Best Case performance, indicating that modeled communication infrastructure is also among the suitable communication infrastructure models for this application.

Figure 6.10a showing the voltage profile for the selected buses in the system indicates that overall the voltage on all these buses remained under limits. This is mainly due to a low average communication delay (150 ms) during transmission of network measurements and control set points as shown in Figure 6.10c. To keep the voltage under limits, the controller curtails the power of PVs causing violations. When controller is not lagging behind, due to efficient communication infrastructure, in this case, could result in a large power to be curtailed (10 kWh on average) from PVs, as shown in Figure 6.10b. Few voltages limit violations (Figure 6.10d) and a small variation in voltage profile can be seen overall (higher than Wired 1 *Gbps* case above) but a small variation.

Powerline Communication Technology

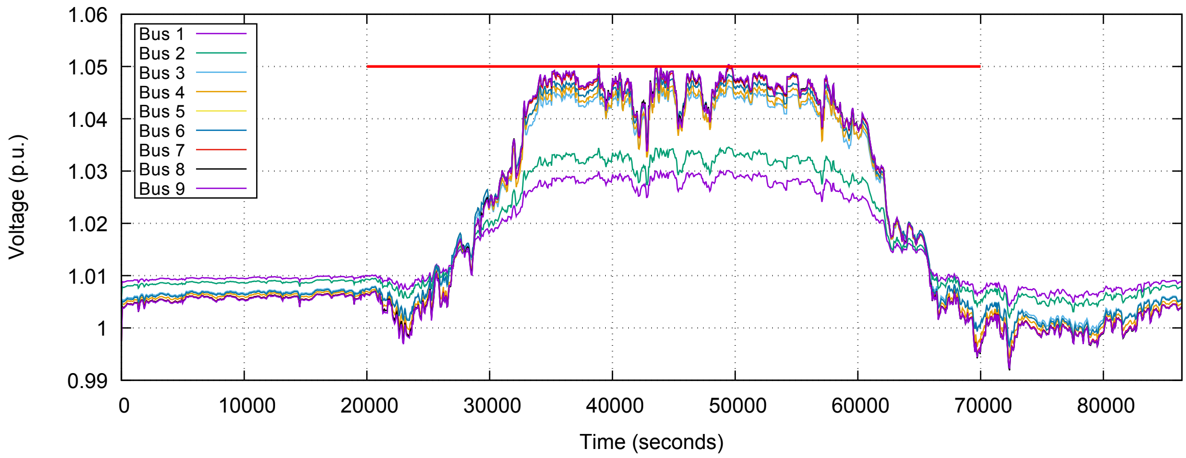
Powerline Communication (PLC) represent a set of technologies that uses electrical cables as medium for data transmission in medium and low voltage electrical networks, and are therefore, considered the natural candidates for implementing Smart Grid applications. However, PLC is a slow and harsh medium and has considerably low bandwidth, compared to wired and wireless technologies. Due to their importance, three variations of PLC are modeled for communication infrastructure, using PLC 1 $Mbps$, PLC 128 *kbps* and PLC 33 *kbps*. The results from these scenarios are presented in Figure 6.11, 6.12 and 6.13 respectively. All these results, overall show larger violations indicating that these are not suitable, under specified requirements, for this case study.

For PLC 1 *Mbps*, a large average communication delay (Figure 6.11c) has caused the controller to lag behind, resulting in increased voltage limit violations and variations, as can be seen in Figure 6.11a, Figure 6.11d and Figure 6.11d. The curtailed power has decreased, on average, to approximately 27% from Best Case. The results of other two communication infrastructure models (PLC 128 *kbps* and PLC 33 *kbps*), in Figure 6.12 and 6.13, show that using these communication infrastructure model, the controller is unable to keep the voltage under limits. Figure 6.12b and 6.13b, show a large communication delay (1.25 *sec* and 1.5 *sec*) that is causing the controller to lag behind and thus is unable to perform its intended function. The reason of large delay is considerably low bandwidth and the use of bus topology. As expected, in both cases, average curtailed power has decreased approximately 80% (in PLC 128 *kbps*) and 95% (in PLC 33 *kbps*) from Best Case.

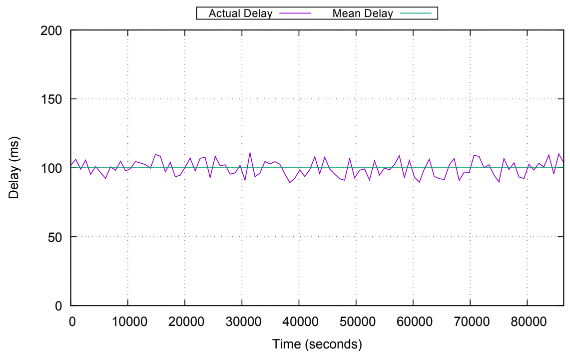
6.6.3 Communication Failure

Due to dependence of control system on communication infrastructure, any communication failures could result in a degraded performance, and in some cases leads to failures. It is therefore, necessary to be able to access the effects of communication failures and to plan accordingly. The tool-set is capable of such insight and to show its capabilities, two scenarios are simulated. In these scenarios, Wired 1 *Gbps* is changed so that nearest (PV_1) and farthermost (PV_6) PV systems would experience a communication link failure.

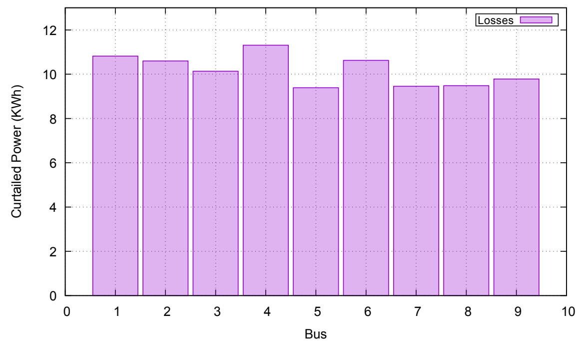
Figure 6.14 shows the results of co-simulation when communication link between PV_1 and controller is failed. The results suggest that the effect is local and resulted in more voltage violations and low power curtailment at the bus where PV_1 is connected. Similarly, Figure 6.15 shows the results of co-simulation when communication link between PV_6 and controller is failed. The results are very similar to PV_1 failure case and also suggests that a local effect, resulting in more voltage violations and low power curtailment at the bus where PV_6 is connected.



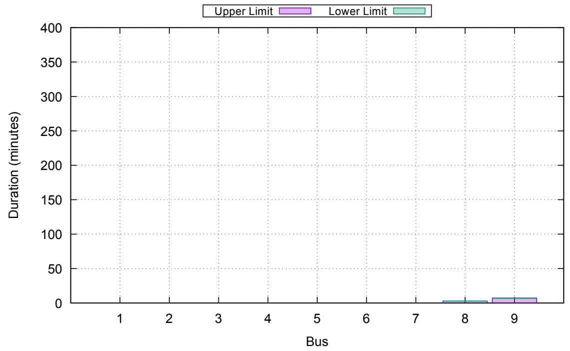
(a) Voltage profiles over time of the selected buses in the system.



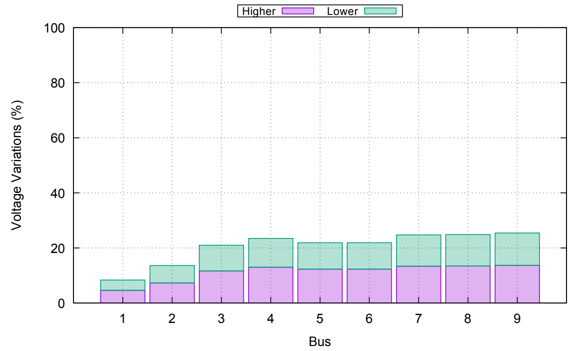
(b) Communication delay over time.



(c) Resulting curtailed power on the selected PVs.

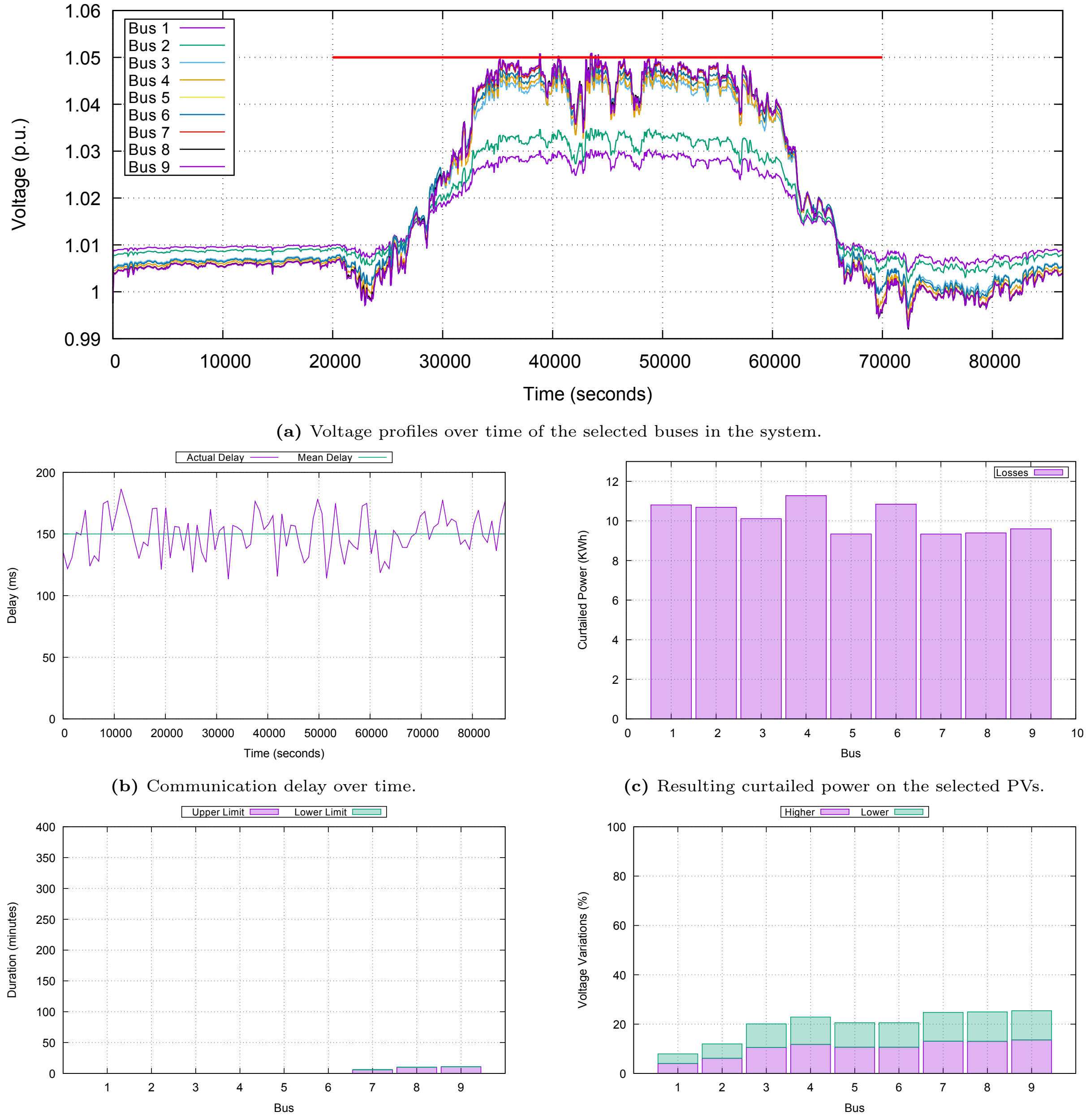


(d) Voltage limits violations on the selected buses.



(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

Figure 6.9: Results of the co-simulation when communication infrastructure is modeled as Wired 1 *Gbps*. The results are showing voltages profiles, accumulated and overtime curtailed power, voltages violations and voltage variations.



(a) Voltage profiles over time of the selected buses in the system.

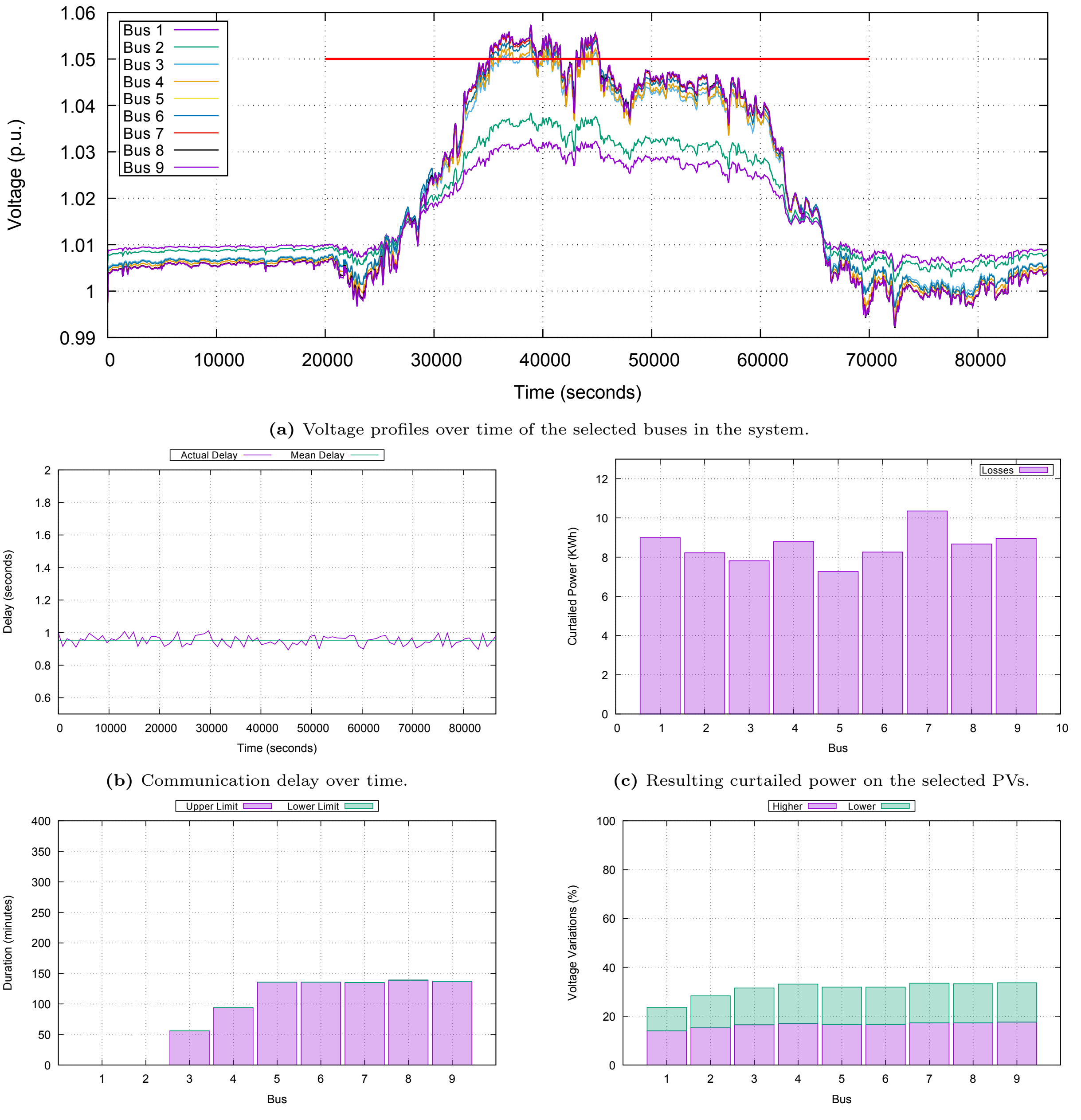
(b) Communication delay over time.

(c) Resulting curtailed power on the selected PVs.

(d) Voltage limits violations on the selected buses.

(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

Figure 6.10: Results of the co-simulation when communication infrastructure is modeled as Wireless 54 $Mbps$. The results are showing voltages profiles, accumulated and overtime curtailed power, voltages violations and voltage variations.



(a) Voltage profiles over time of the selected buses in the system.

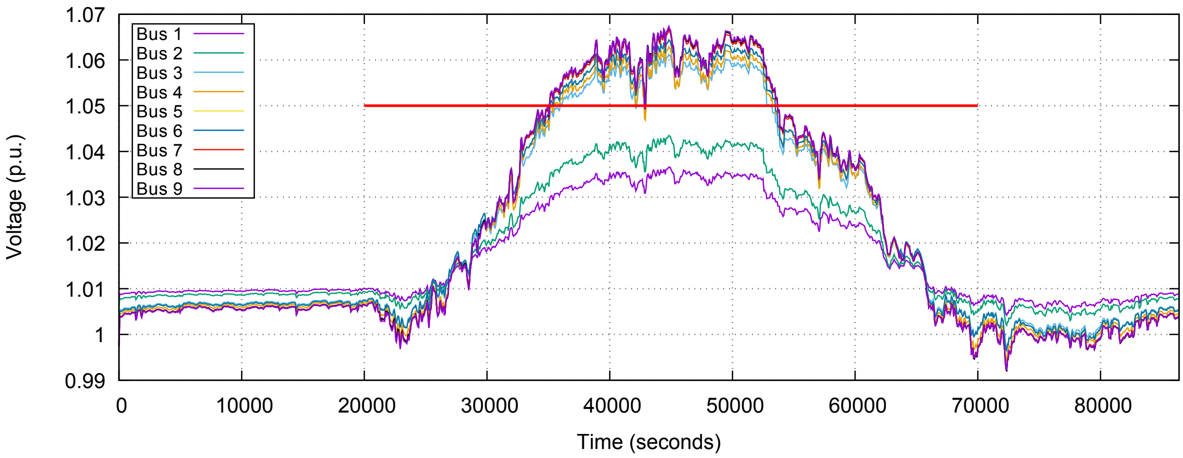
(b) Communication delay over time.

(c) Resulting curtailed power on the selected PVs.

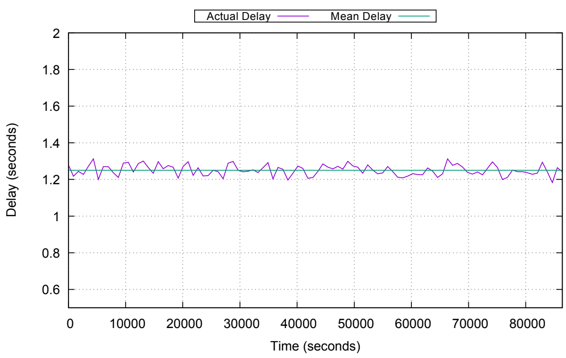
(d) Voltage limits violations on the selected buses.

(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

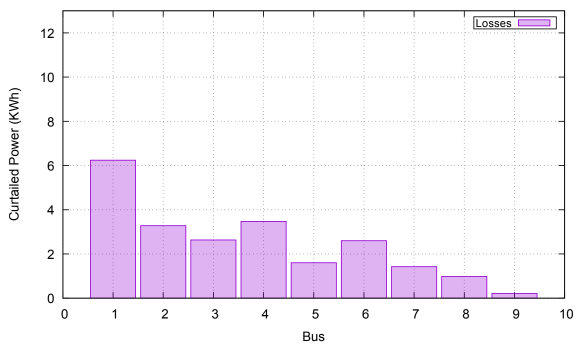
Figure 6.11: Results of the co-simulation when communication infrastructure is modeled as PLC 1 *Mbps* Broadband Powerline communication. The results are showing voltages profiles, accumulated and overtime curtailed power, voltages violations and voltage variations.



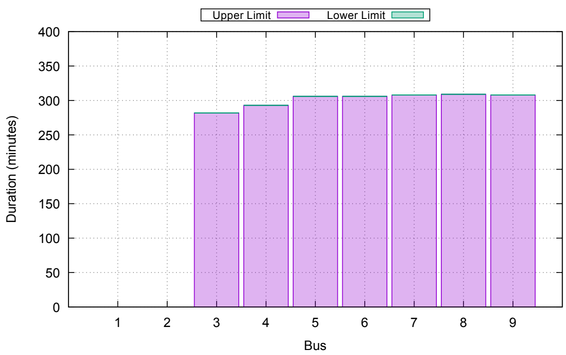
(a) Voltage profiles over time of the selected buses in the system.



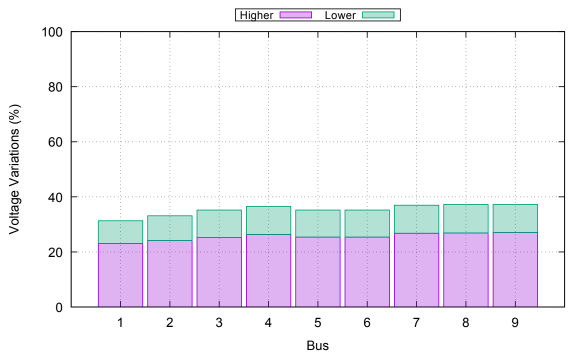
(b) Communication delay over time.



(c) Resulting curtailed power on the selected PVs.

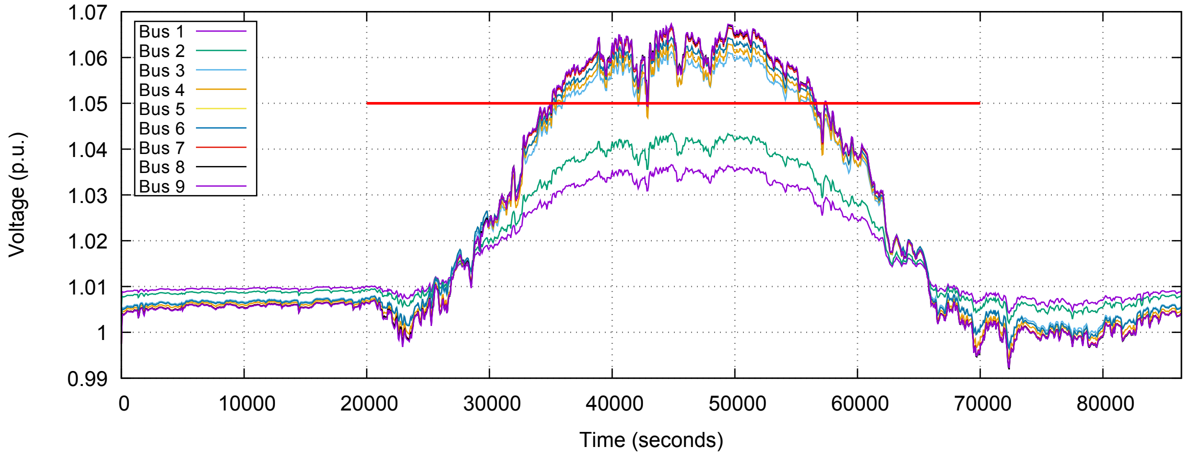


(d) Voltage limits violations on the selected buses.

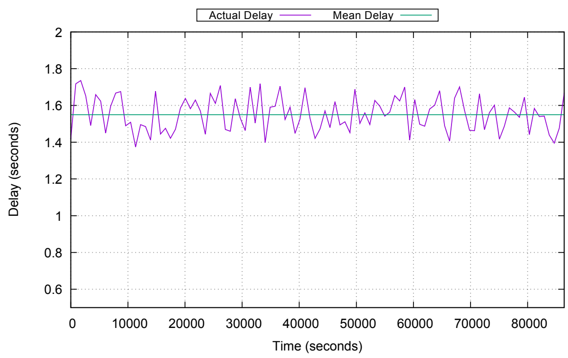


(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

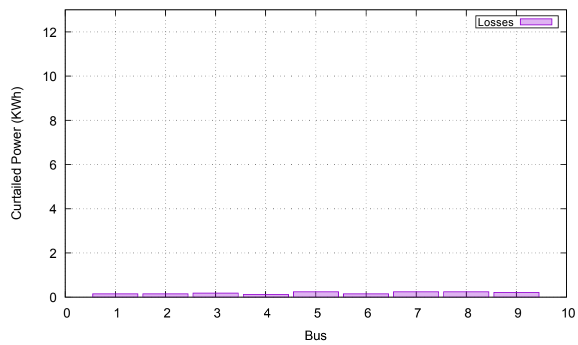
Figure 6.12: Results of the co-simulation when communication infrastructure is modeled as PLC 128 *kbps* Powerline communication. The results are showing voltages profiles, accumulated and over-time curtailed power, voltages violations and voltage variations.



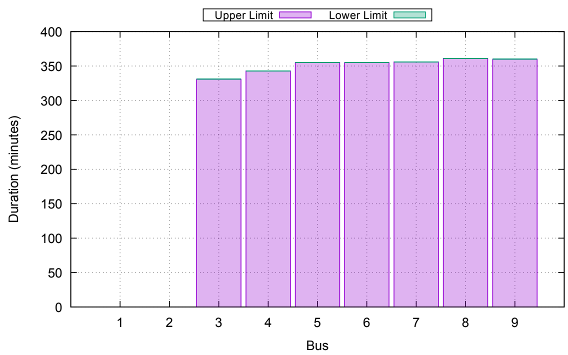
(a) Voltage profiles over time of the selected buses in the system.



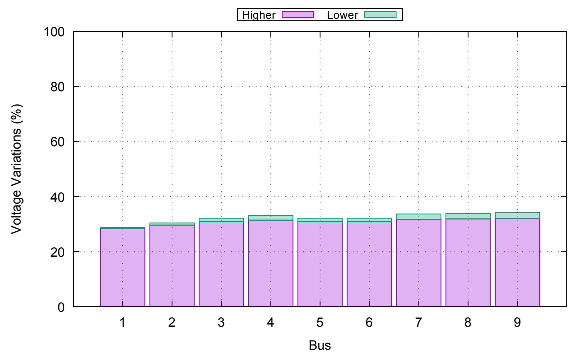
(b) Communication delay over time.



(c) Resulting curtailed power on the selected PVs.

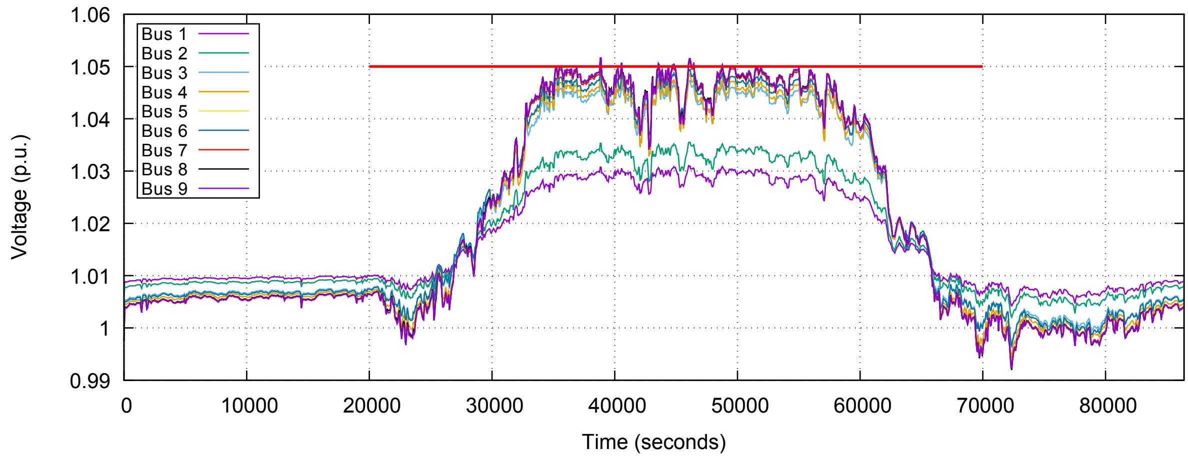


(d) Voltage limits violations on the selected buses.

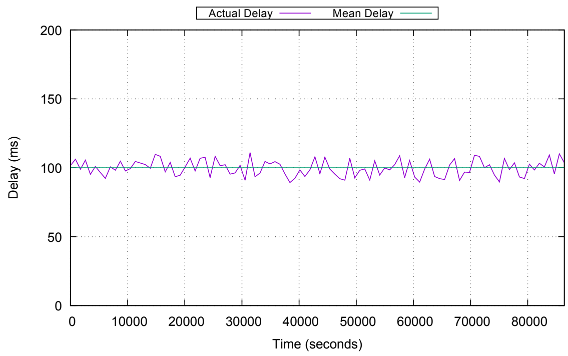


(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

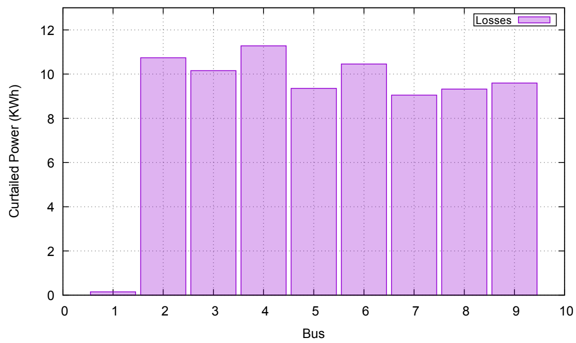
Figure 6.13: Results of the co-simulation when communication infrastructure is modeled as PLC 33 *kbps* Powerline communication. The results are showing voltages profiles, accumulated and over-time curtailed power, voltages violations and voltage variations.



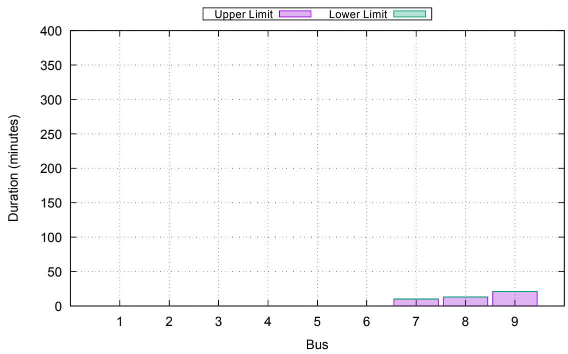
(a) Voltage profiles over time of the selected buses in the system.



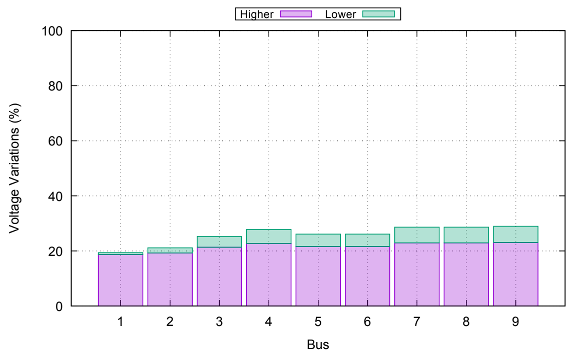
(b) Communication delay over time.



(c) Resulting curtailed power on the selected PVs.

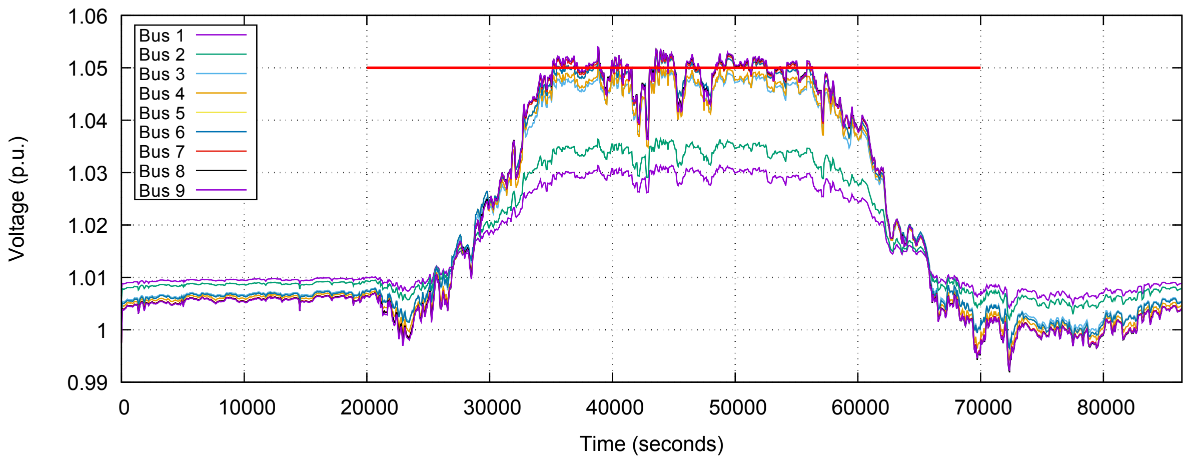


(d) Voltage limits violations on the selected buses.

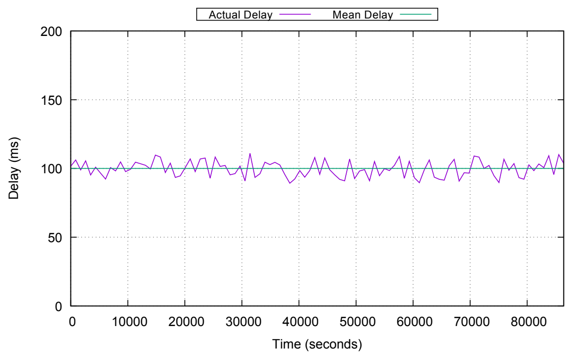


(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

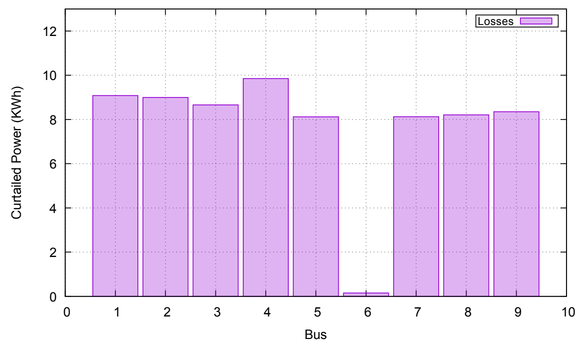
Figure 6.14: Results of the co-simulation when communication infrastructure is modeled as PV_1 (nearest node) experiencing a communication link failure. The results are showing voltages profiles, accumulated and overtime curtailed power, voltages violations and voltage variations.



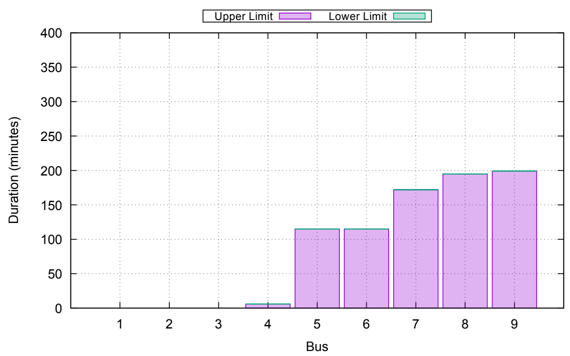
(a) Voltage profiles over time of the selected buses in the system.



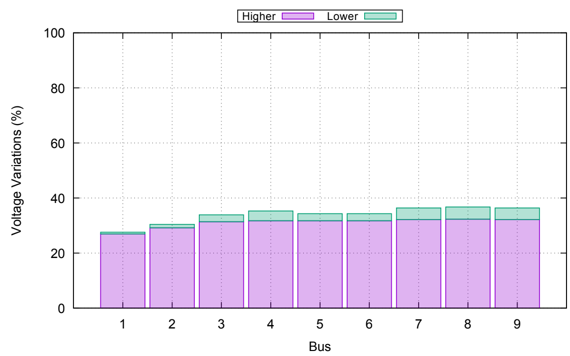
(b) Communication delay over time.



(c) Resulting curtailed power on the selected PVs.



(d) Voltage limits violations on the selected buses.



(e) Percentage of voltage variations w.r.t the Best Case on selected buses.

Figure 6.15: Results of the co-simulation when communication infrastructure is modeled as PV_6 (farthermost node) experiencing a communication link failure. The results are showing voltages profiles, accumulated and overtime curtailed power, voltages violations and voltage variations.

6.7 Summary

This chapter has presented the second case study to show the effectiveness and applicability of the proposed tool-set. The case study shows a Smart Grid application to introduce fairness, when using active power curtailment approach for voltage regulation. The controller, after receiving measurements from installed PVs, calculates the safe maximum active power that can be allowed to be injected into the distribution network. This makes voltage regulation highly dependent on communication infrastructure for carrying measurement and control commands. An analysis of communication infrastructure models with varying communication technologies and scenarios are modeled and analyzed with proposed tool-set to measure performance and effects. In this case study, the power system model is a 0.4kV residential low voltage network modeled and simulated with DIgSILENT PowerFactory. The centralized coordinated controller is implemented in Python while communication infrastructure models are developed with OMNeT++. For co-simulation power system, Python and OMNeT++ are coupled with custom interfaces that use TCP sockets for intra-simulator communication. A description of results along with graphs showing voltage profile and calculated KPIs are also presented.

7 Case Study III – Distributed Voltage Regulation using Multi-agents System and AI in a Medium Voltage Distribution Network

In previous two chapters, the first and the second case studies are presented that described communication infrastructure analysis for two Smart Grid innovative applications, with varying parameters and scenarios. This chapter presents the third case study where communication infrastructure analysis for a consensus based distributed voltage regulation algorithm is performed. The co-simulation environment consists of domain specific simulator (DIgSILENT PowerFactory, Python, JADE and OMNeT++) coupled using custom interfaces. Figure 7.1 highlights the identified requirements, addressed in this case study.

This case study presents another innovative Smart Grid application addressing distributed voltage regulation in a medium voltage distribution network. The distributed energy resources (DERs) are modeled as autonomous intelligent agents that interact with neighbors, under the supervision of a coordinating agent, to negotiate on the optimal reactive power values to support in voltage regulation.

The chapter starts with Section 7.1 presenting an introduction and some background of voltage regulation in distribution network using a distributed control scheme. Section 7.2 presents the suitability and design of the case study. Section 7.3 presents an introduction to multi-agents system and its applications in the power systems. Modeling of power system and distributed control system are described in Section 7.4. The description of communication scenarios are presented in Section 7.5. The co-simulation concept, tools and interfaces are described in Section 7.6. Results from individual simulation scenarios are presented in Section 7.7. The chapter concludes with a summary in Section 7.8.

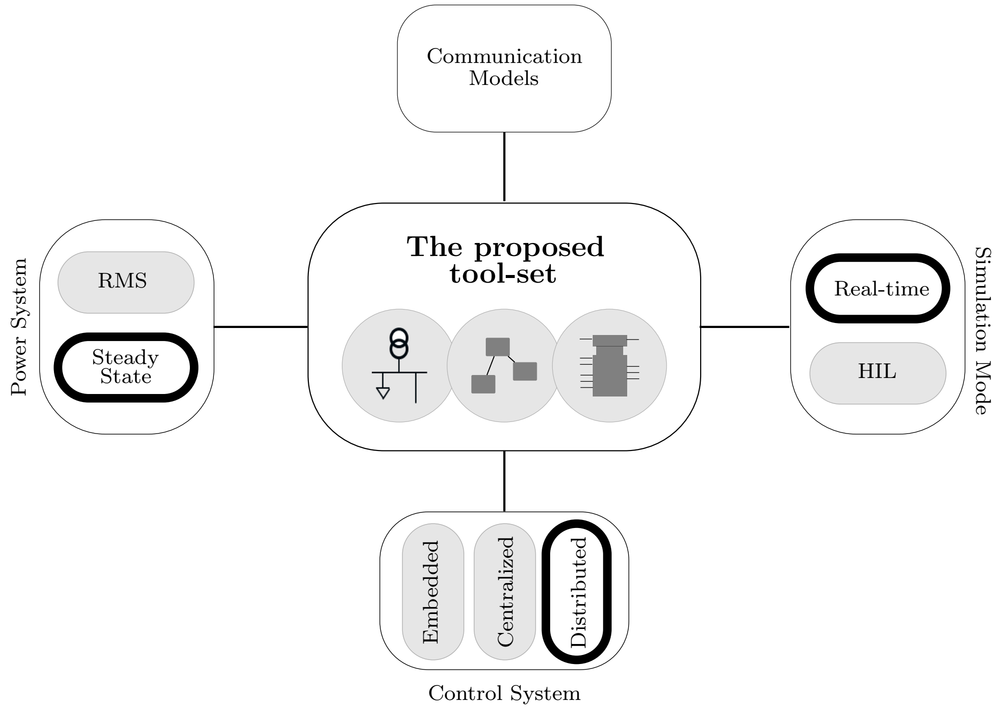


Figure 7.1: Parts of requirements addressed in co-simulation environment for this case study.

7.1 Background

Efforts to modernize the power systems has gained a lot of momentum during the last few years mainly influenced by environmental concerns, economic, technological and political interests. These efforts have objects such as reducing greenhouse gas emissions by increasing share of renewable energy resources etc. The implementation of such efforts are being considerd the future of power system and termed as the Smart Grid. The use of renewable energy resource for power generations have many advantages over the transitional nonrenewable resources such as the reduction of transmission losses as they can be placed near load centers due to their relatively small size, green energy due to low greenhouse gas emissions, less dependency on depleting fossil fuel resources etc.

Increased hosting of distributed generation poses some technological challenges. The output of the traditional nonrenewable based power generators can be controlled according to demand. But, renewable energy resources having intermittent and variable generation that is hard to predict accurately, are less likely to respond to the generation requests, adequately. This could lead to situations where generation can be higher at the time of low demand and low at the peak demand. These situations require new control strategies capable of ensuring the grid stability and reliability along with power quality [RVRJ11].

The voltage has to be supplied to connected loads fulfilling some suitable upper and lower limits as specified for example in standards such as EN 50160. Traditionally, a centralized voltage regulation equipment such as OLTC, shunt capacitor etc. employing the line drop compensation method, have been used for voltage regulation. But in a distribution system with lager number of distributed generators, such methods may not be efficient because the system voltage is no longer dependent on load only but also one distributed generators as well [KCM15]. An attractive alternative is thus the distributed voltage regulation, where distributed generators are operated in a coordinated autonomic manner and their power compensation abilities are exploited.

7.2 Suitability and Design

This case study analysis the performance of a distributed voltage regulation algorithm in a medium voltage distribution network. This case study is selected as to demonstrate the usability of analysis methodology for distributed control applications. The conducted analysis is helpful in providing important insights into the interdependencies of domains. This insight could be further not only helpful in designing better systems but also understanding the communication infrastructure requirements for such applications.

The control algorithm is consensus based and is implemented using autonomous agents in a multi-agents system. A modified medium voltage IEEE 37-bus Feeder system with four distributed generators are used as the model for power system. Whenever there is a voltage violation, the affected DG monitoring agent triggers the algorithm for the calculation of optimal reactive power for each of the four agents representing the DGs. Agents then communicated with neighbors for reaching on the consensus for their local optimal reactive power set points. Since agents use communication infrastructure for communicating with neighbors making the performance of control algorithm highly dependent on the communication infrastructure parameters such as bandwidth, latency, communication technology etc. This makes it necessary to evaluate the performance of the control algorithm in different communication scenarios.

There are number of different communication technologies and some of them are mentioned in Table 2.4. This make many possibilities for the implementation of communication infrastructure. Further, each technology has its own characteristics and performance that may or may not match with the specific deployment requirements. A tool capable of simulating the alternative technologies is therefor very valuable to access the performance of system under different communication technologies. Sharing a communication channel with multiple application and service would also be of interest as it may not be feasible solution to use a dedicated communication infrastructure for every other deployed application in the same or neighboring network.

This case study features a distributed consensus-based voltage regulation algorithm with a steady state power system simulation and is selected to shows the effectiveness of proposed co-simulation based tool-set for analysis of such Smart Grid applications.

7.3 Agent and Multi-agents System

There is still no unified definition of an agent (see Section 3.3.3 for a basic definition), however there are certain characteristics that an agent possess – autonomy, adaption and cooperation. These characteristics, shown in Figure 7.2, makes the agent an autonomic entity that can not only react to changes in its environment but can change its behavior (adapt to changes) and can interaction with its neighbors for the fulfillment of its design goals. Two or more agents make a Multi-agents System (MAS). The agents' emergent properties makes multi-agents system suitable for designing flexible, fault tolerant and extensible system. This fact has made them attractive for many power system applications as well [MDC^{+}07a].

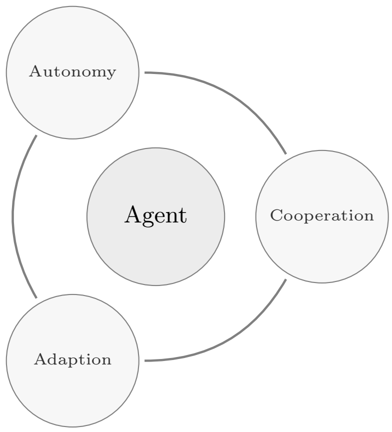


Figure 7.2: An agent's properties; making it an autonomic entity, not only reacting to changes in its environment but changing its behavior, and can interacting with neighbors for the fulfillment of design goals.

Foundation for Intelligent Physical Agents (FIPA) [211] is an IEEE standards organization mandated for developing the open standards for promoting interoperability between Multi-agents System, developed by different entities and with other systems. These standards are considered the *de facto* standards for multi-agents system development. FIPA defines the Agent Management Reference Model (Figure 3.7) that provides a logical reference model about how the agent exist and operate. There are six logical components including an agent(s), a directory service utility agent providing discovery services to other agents, agent management utility agent that controls the agents and their interaction with application platform, a message transport service providing the communication methods for agents. Agents in a multi-agents system use messages coded with a language to communicate with each other. FIPA-ACL (FIPA Agent Communication Language) is part of FIPA standards and is widely used. Each agent message consists of two components; the content (syntax) and the ontology (semantics). FIPA standards has proposed four content languages, suitable for different ontological representations [MDC^{+}07b].

7.4 Modeling

Modeling is a well know technique for analyzing and predicting the effects of changes on a real-world system using its simplified representation. It is the first phase in the methodology (Figure 4.2). Models developed at this phase are used later for co-simulation study. This section describes the modeling of power and distributed control system modeled with the DIgSILENT PowerFactory and JAVA Agent DEvelopment framework (JADE) respectively. Key Performance Indicators (KPIs) of interest are specified to be calculated for the quantification of results and comparison of scenarios.

7.4.1 Power System

Although, there are many tools for modeling of power system, DIgSILENT PowerFactory [205] is selected due to its features such as flexibility, extendability, wide coverage of power system ares, large library of models and many more. It is a sophisticated highly specialized proprietary software for modeling and dynamic simulation of power system. The modeled power system is a modified IEEE 37 Node system and depicted in Figure 7.3. This medium voltage 4.8 kV distribution system consists of many distributed energy resources. The technical details of model are available from IEEE Power & Energy Society [218].

7.4.2 Distributed Controller

For implementing distributed controller Multi-agents System paradigm is used. Since an agent poses the properties such as autonomy, adaption and cooperation, that makes them ideal for distributed control applications. The distributed algorithm for providing voltage support is a consensus algorithm based on [DGH10, OSFM07, OS06]. The agent monitors voltage changes in magnitude and angle due to any variation in the active and reactive power. Once a voltage limit violation is detected the *agent* then calculates the required change in reactive power by using Equation (7.1).

$$\delta V = S \delta Q \tag{7.1}$$

where $S = J_{qv}^{-1}$ is inverse of Jacobian matrix obtained after power flow which is also known as voltage sensitivity matrix.

The agent (i) then communicates this value to its neighbors (n_i) after dividing the value by n. Each neighboring agent (j) of leader agent (i) again calculates the values and send it to its neighbors (n_j). According to this algorithm, each agent (x) in the multi-agents system (M) maintains a value $\psi_x[\eta]$ and updates it is with each iteration according to Equation (7.2), considering D_x as the out-degree of agent x. One possible communication scenario with six agents is depicted in Figure 7.4. For communication the agents use the FIPA's Contract Net Interaction Protocol [209].

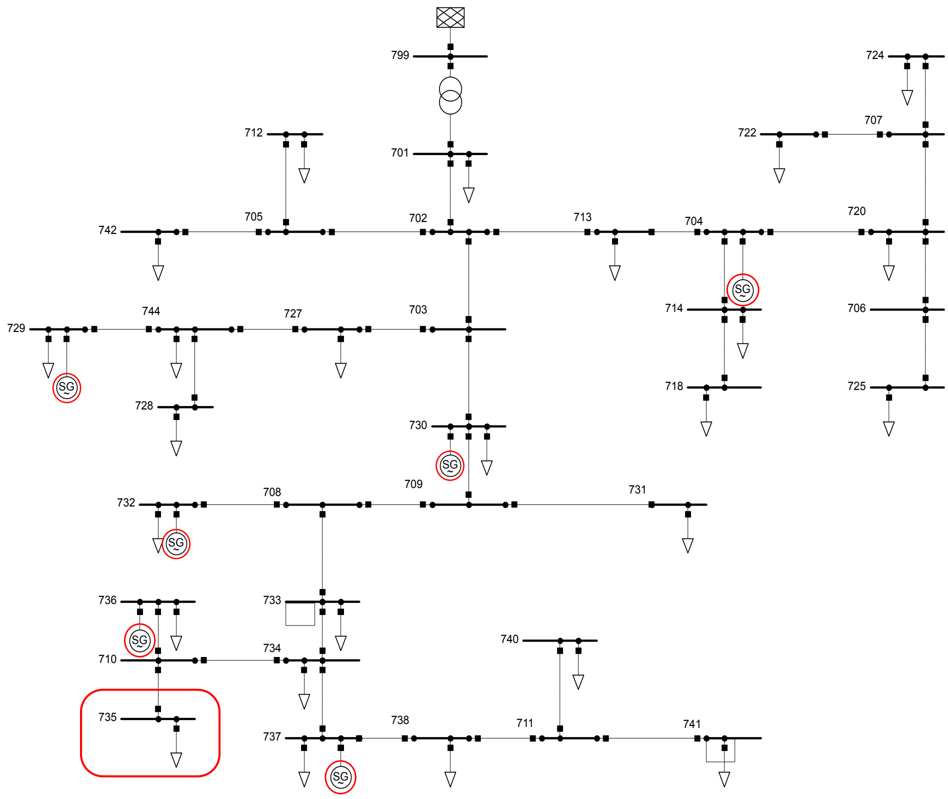


Figure 7.3: Power system model. The modified IEEE 37-bus Feeder system modeled in DIgSILENT PowerFactory. Six distributed generators implementing the distributed voltage regulations algorithm are identified with read circles. Bus 735 is selected having critical voltage, after many experiments.

$$\psi_x[\eta+1] = \frac{1}{1+D_x}\psi_x[\eta] + \sum_{y\in n_j}\frac{1}{1+D_y}\psi_y[\eta] \tag{7.2}$$

7.4.3 Key Performance Indicators (KPIs)

Key Performance Indicators (KPIs) are some measurable quantities and are used to quantify and measure the performance. In the analysis methodology, KPIs are used for comparing different communication infrastructure and the performance of control and power systems. These KPIs are highly application dependent. For this case study two KPI – Voltage Variation and Voltage Violations – from power system are specified to be calculated for each simulation scenario.

Voltage variation KPI is calculated as per Equation (5.1) and measures the voltage deviations on the selected buses with respect to the Best Case (with ideal communication). While Voltage Violation KPI is calculated using Equation (5.3) and sum the duration of voltage violations.

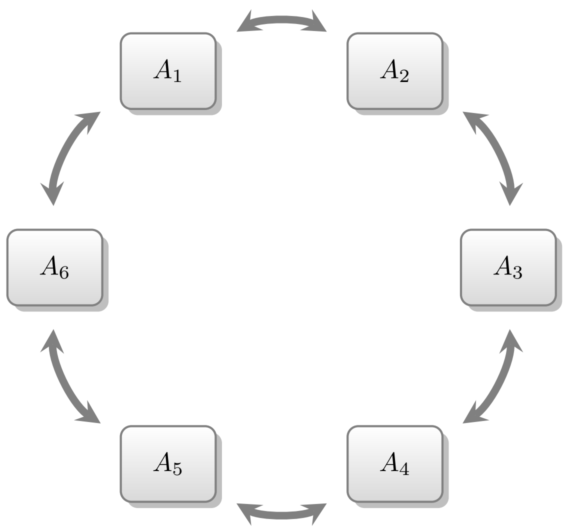


Figure 7.4: One possible agent communication scenario with six agents. Neighboring agents communicate with each other to reach on a consensus. In this case, agent A_1 communicates with agents A_6 and A_2, agent A_2 communicates with agents A_1 and A_3 while A_6 communicates with agents A_1 and A_5 and so on.

7.5 Communication Scenarios

To evaluate the performance of control system and its effects on underlying power system when different communication infrastructure are used, number of communication infrastructure are modeled with varying parameters, technologies and scenarios. In addition to these modeled scenarios, two reference scenario are used to measure the best and the worst performances and used later for comparisons and KPIs calculations.

7.5.1 Reference Scenarios

Two reference scenarios are modeled to access the system performance with the best and the worst communication conditions. The Best Case and the Worst Case scenarios are modeled with communication infrastructure being the ideal for communication – with infinite bandwidth and negligible latency – and worst – no more communication possible – to be simulated together with power and control system models. These scenarios not only provide the best case and worst case performance of control system and help in seeing its effects on underlying power system, but results of these scenarios are used further for the calculation of KPIs for other communication infrastructure models.

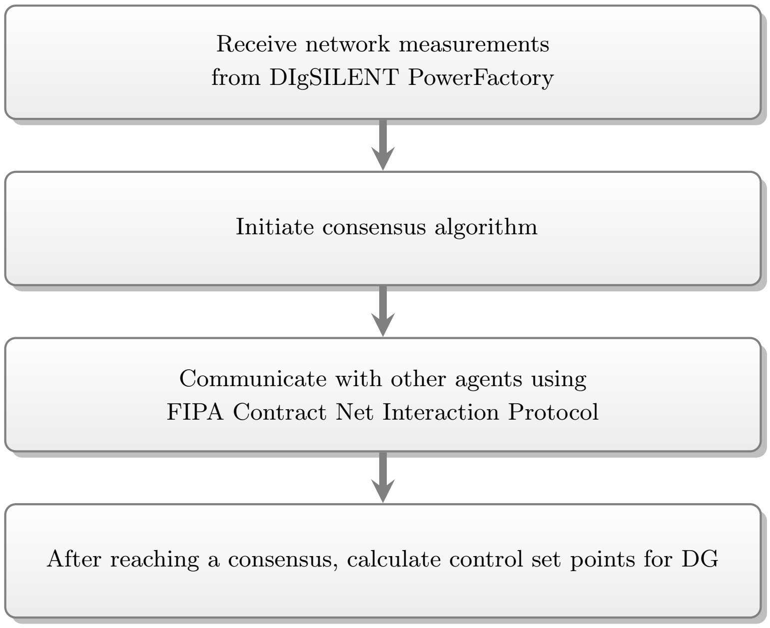


Figure 7.5: Major steps in consensus based voltage support algorithm implemented in the JADE agent.

7.5.2 Modeled Communication Scenarios

The specified communication scenarios are listed in Table 7.1, below. Communication model is created for each of the specified scenario in the OMNeT++ and later used in co-simulation.

7.6 Co-simulation

The analysis of communication infrastructure and its effects on the performance of control and power system are evaluated using a co-simulation environment consisting of four domain specific tools. The tools are coupled and data is exchanged during simulation with the help of some custom interfaces. The power system simulator DIgSILENT PowerFactory is controlled by a Python script while the other two simulators are running in parallel. The co-simulation is running in real-time synchronized with the system clock. Rest of this section first presents a conceptual overview of the co-simulation, then a description of the tool and developed interfaces is presented next.

7.6.1 Concept

The case study is about solving the voltage limits violations in a power system model having multiple distributed generators. The control algorithm is implemented as multi-agents system. A Python script controls the steady-state power system simulation that is being constantly monitored by the agents. For this purpose, the agents receive measurements from network through communication infrastructure. Once a violation is detected, the agent (leader agent) triggers the

Table 7.1: Communication Scenarios

Category	Name	Description	Model
Technology	Wired	Two variation of wired communication technology with 40 and 1 *Gbps* bandwidths, a star topology and TCP/IP over Ethernet.	Figure A.12
	Wireless	An infrastructure wireless communication technology (IEEE 802.11g) where Access Points are connected with a wired communication technology having 1 *Gbps* bandwidth.	Figure A.13
	PLC	Three variations of Powerline communication with 1 *Mbps*, 128 *kbps* and 33 *kbps* bandwidths (IEEE 1901.1)	Figure A.14
Sharing	Channel Sharing	Sharing of channel with other services	Figure A.15

control algorithm and calculates the required active power. It then initiates a communication with its neighboring agents sending them the calculated values again using the communication infrastructure. The neighboring agents then do the same until the control algorithm reaches to a consensus on the value of required reactive power support. A conceptual overview of the co-simulation is depicted in Figure 7.6.

7.6.2 Simulator Coupling and Interfaces

Four tools/simulator have been used in the co-simulation. These tools are mostly using the custom built TCP/IP interfaces except between Python and DIgSILENT PowerFactory. Details of the tools and custom interfaces is presented below.

DIgSILENT PowerFactory

DIgSILENT PowerFactory is a powerful dynamic simulation platform for power system analysis. A brief of its capabilities is described in Section 5.5.2. The DIgSILENT PowerFactory has an API interface that can be accessed from many different languages including Python. This interface is used through a Python script for a steady state simulation. A schematic overview of the interface in depicted in the Figure 7.8.

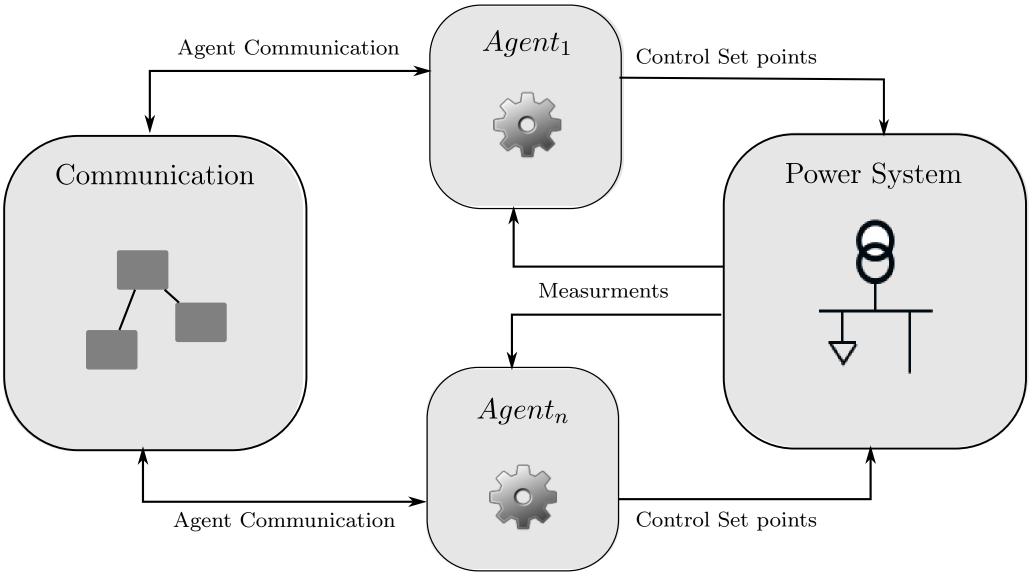


Figure 7.6: Conceptual overview of the co-simulation. Agents implement distributed control and receive network measurements from the power system and communicated with neighbors using communication infrastructure to reach on a consensus.

Python

Python [230] is a cross-platform, powerful, object-oriented, interpreted language with clean, simple and compact syntax. Python is chosen to control DIgSILENT PowerFactory steady-state simulation due to ease of implementation. The DIgSILENT PowerFactory provides Python packages using which the API interface can be accessed. Furthermore, to communicate with other simulators (JADE in this case), Twisted [235] networking engine is used to provide a TCP/IP socket interface. Figure 7.9 depicts an overview of the interface and major components.

JAVA Agent DEvelopment framework (JADE)

Multi-agents System paradigm of problem solving requires number of domain independent issues to be addressed when adopted for solving a specific problem. Writing custom code for handling these issues is an expensive option. Instead, a better option is to use a middleware such as the JADE for developing a multi-agents system based solution. JAVA Agent DEvelopment framework (JADE) [222] is a widely used open source distributed middleware framework that facilitates the multi-agents system development by providing a domain independent infrastructure. The infrastructure is easily expendable with add-on modules. The run-time environment implements the complete agent life-cycle support functionalities, agent logic and set of graphical tools for controlling, monitoring and logging the execution. The JADE is fully compliant with FIPA specification, in fact, validation of FIPA specification was the primary motivation of the JADE's development [BCG07].

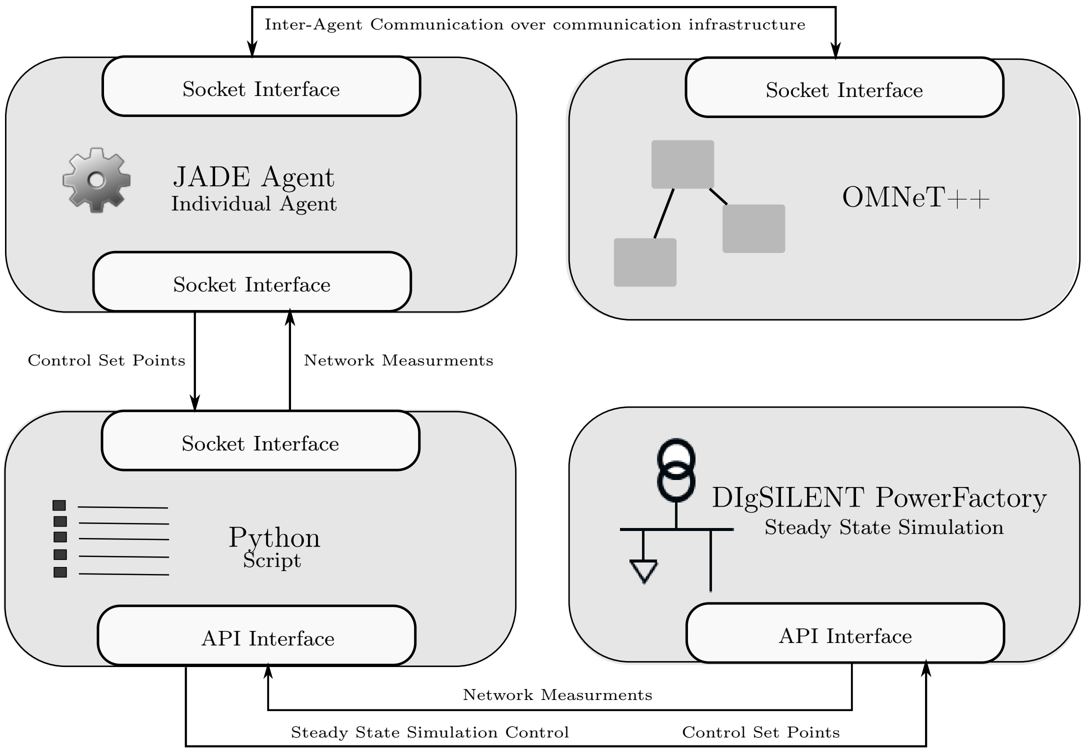


Figure 7.7: Co-simulation setup and interfaces. Agents implement distributed control algorithm and receive network measurements from the power system and communicated with neighbors using communication infrastructure to reach on a consensus.

Although, JADE has a "Socket Proxy Agent" for socket communication but the functionality is not sufficient for the requirement of this case study. Thus, a flexible custom socket interface is implemented. Figure 7.10 shows an overview of the implemented interface. The interface contains two agents; one implementing the consensus algorithm while other provides the socket interface for communicating with other simulators. The two agents communicate using the FIPA Contract Net Protocol. The interface is used to represent a distributed generator.

OMNeT++

OMNeT++ is the communication infrastructure simulator and is the integral part of co-simulation environment. It is a popular open-source discrete event simulation platform widely used for communication, multiprocessor, distributed and parallel system modeling and simulations. Development of a custom interface for data exchange over TCP/IP sockets is described in Section 5.5.2. This case study utilizes the same interface for coupling with JADE agents.

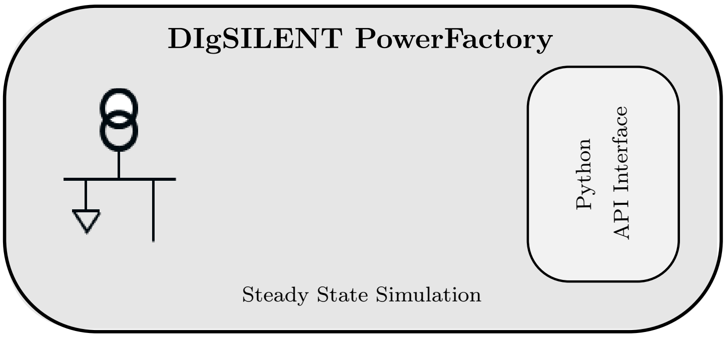


Figure 7.8: The DIgSILENT PowerFactory interface implemented using its Python API.

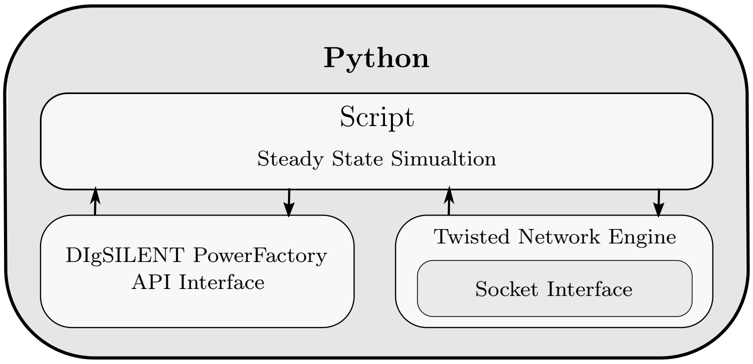


Figure 7.9: The Python interface with three major component; algorithm for calculating the load flow and controlling stead state simulation, DIgSILENT PowerFactory API module for interfacing with DIgSILENT PowerFactory and Twisted network engine for socket interface.

7.7 Results

This section presents the results for the performance investigation of the Smart Grid application with varying communication infrastructure parameters, technologies and scenarios. The quantified results in the form of KPIs calculated from the power and communication systems are also described.

7.7.1 Algorithm Convergence Time

Table 7.2 and Figure 7.11, below lists and shows the convergence time of distributed consensus algorithm when simulated with varying communication infrastructure parameters, technologies and scenarios. In the Best Case, the convergence time is zero as in this case, ideal communication with infinite bandwidth and negligible latency is assumed. Since, the algorithm is consensus based and requires that the agents coordinate with their neighbors which is not possible when there is no communication link, that is why the convergence time is infinity (∞). The results

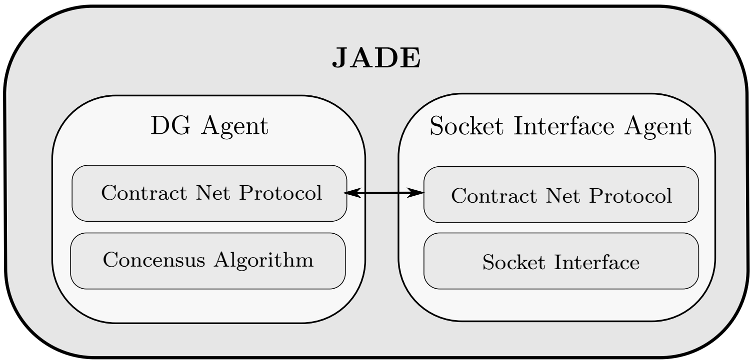


Figure 7.10: Two JADE agents are working together for implementing the distributed control algorithm and a socket interface. DG Agent runs the consensus algorithm receives the network measurements through the Socket Interface Agent that implements a custom socket interface. Agent are using FIPA Contract Net Protocol for communication.

show a non-linear behavior but further suggests that the convergence time is highly affected by communication infrastructure parameters.

Table 7.2: Algorithm convergence time.

S.#	Scenario Name	Time
1	Best Case	0 *sec*
2	Worst Case	∞
3	Wired 40 *Gbps*	32 *sec*
4	Wired 1 *Gbps*	57 *sec*
5	Wireless 54 *Mbps*	79 *sec*
6	PLC BB 1 *Mbps*	290 *sec*
7	PLC NB 128 *kbps*	432 *sec*
7	PLC NB 33 *kbps*	1010 *sec*
8	Channel Sharing over Wired 1 *Gbps*	294 *sec*

7.7.2 Reference Scenarios

Two reference scenarios where communication infrastructure is modeled as the ideal and the worst for communication, are simulated to provide a best case and worst case performance of the distributed control algorithm. The Best Case scenario results are later used to calculate the KPIs for other communication infrastructure models including the Worst Case.

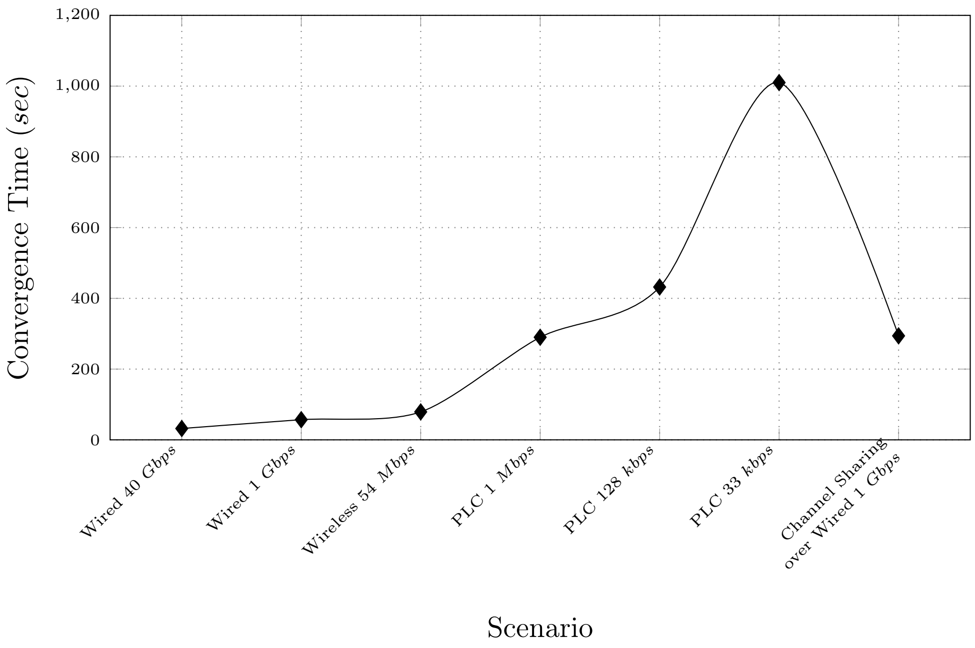


Figure 7.11: Algorithm's convergence time in different scenarios.

The Best Case

Figure 7.12 shows the results for the Best Case – having a communication infrastructure with infinite bandwidth and negligible latency (ideal communication). The results shows that the distributed voltage support algorithm is immediately able to support the voltage, when a lower voltage limit violation is detected.

The Worst Case

Figure 7.13 shows the results for the second reference scenario, obtained by simulating communication infrastructure where agents are no longer able to communicate. As presented in Table 7.2, the convergence time in this case is infinity (∞), resulting in the control algorithm inability to perform its desired function of voltage support and thus the voltage on the bus remains lower (Figure 7.13a) for more than 25 *minutes* (Figure 7.13b). Furthermore, there is about 10 % variations in voltage as compared to the Best Case performance (Figure 7.13c).

7.7.3 Communication Technologies

The communication infrastructure is modeled with varying parameters of three different categories of communication technologies including the wired, the wireless and the Powerline communication. First two results (Figure 7.14 and Figure 7.15) are for wired communication technology with physical bandwidth of 40 *Gbps* and 1 *Gbps*, the next result (Figure 7.16) is for wireless communication

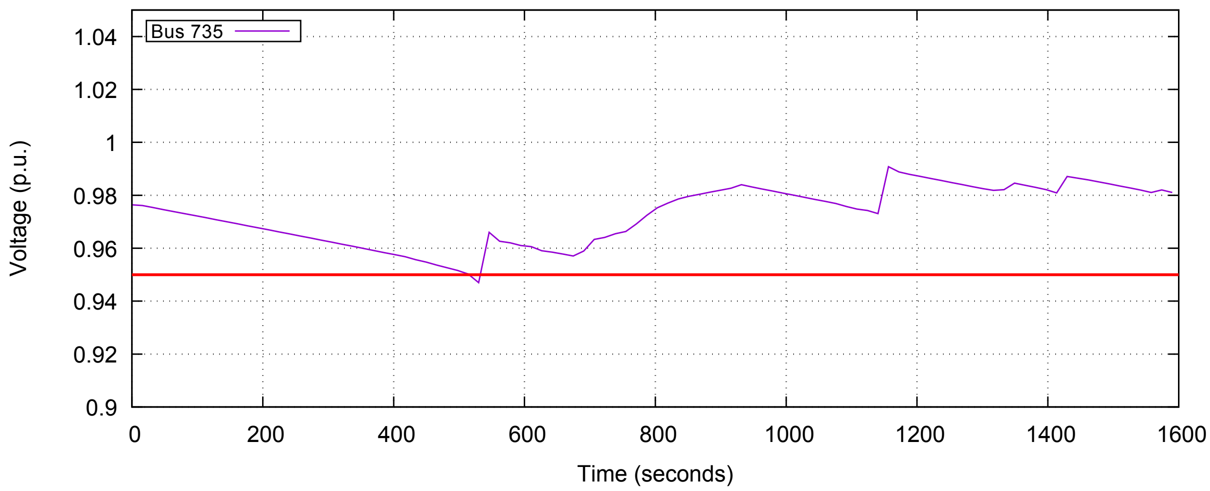


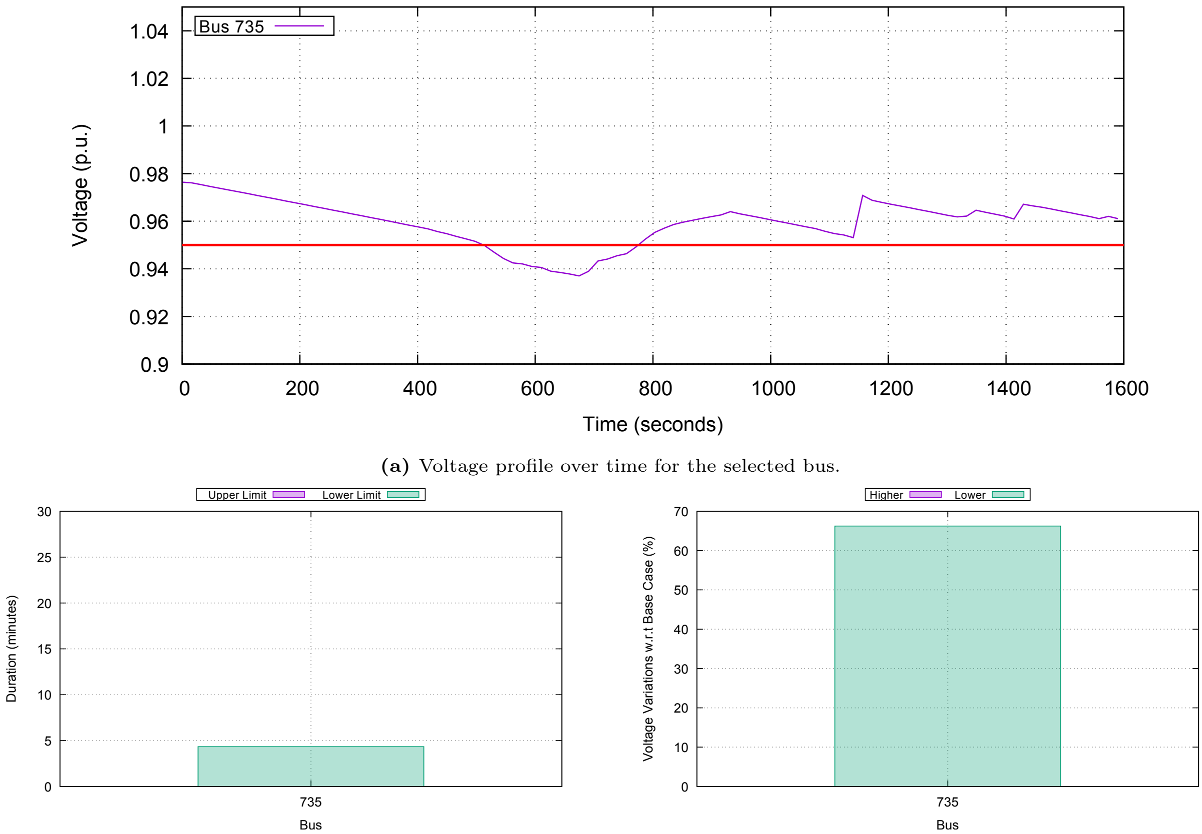
Figure 7.12: The Best Case reference scenario results. The distributed control algorithm is able to support the voltage after reaching to a consensus, immediately. Due to ideal communication used in communication infrastructure, the algorithm's convergence time is zero.

technology IEEE 802.11g, while the next two results (Figure 7.17 and Figure 7.18) corresponds to broadband and narrowband Powerline communication technologies with bandwidth of 1 *Mbps* and 128 *kbps* respectively.

Wired Communication Technology

Wired communication technologies are important for providing a high speed, real-time communication links and have many applications in the Smart Grid. Two variations of wired communication network technology are simulated for communication infrastructure along with power system and distributed controller. Figure 7.14 shows the results for the model with a 40 *Gbps* Ethernet. The distributed control algorithm's convergence time in this case is about 32 *sec* and that is roughly the time bus experiences the voltage limits violations (Figure 7.14b). There are almost no variation in the voltage profile in this case as compared to the Best Case (Figure 7.14b).

Figure 7.15 presents the results of the communication infrastructure modeled with the second variant of wired communication technology. This model has a start topology, 1 *Gbps* of bandwidth, Ethernet at Link layer and TCP/IP as network and transport protocols. Algorithm's convergence time in this case is 57 *sec*. The voltage is supported to be under the limits after a consensus is reached during this time. This process causes the voltage limits violation to stay for a little more than one minute (Figure 7.15b). There also are almost negligible variation in the voltage profile as compared to the Best Case (Figure 7.15b).



(a) Voltage profile over time for the selected bus.

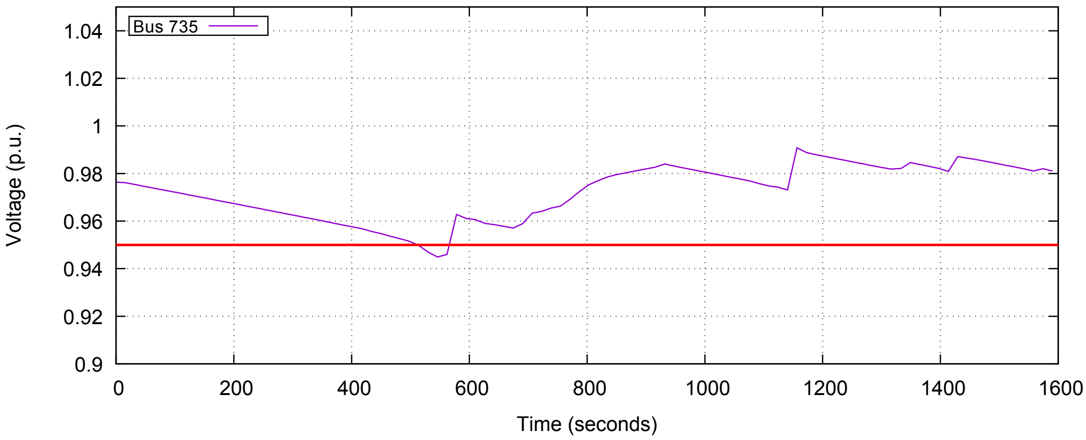
(b) Voltage limits violations on the selected bus.

(c) Percentage of voltage variations w.r.t the Best Case on the selected bus.

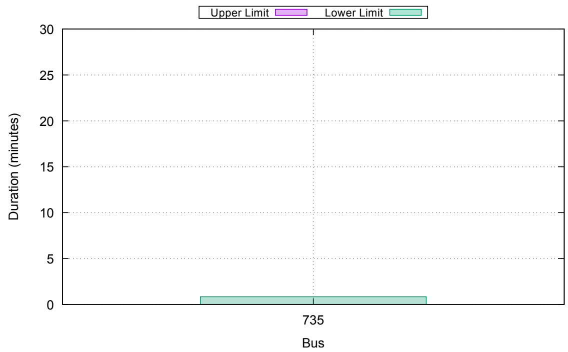
Figure 7.13: The Worst Case reference scenario results. Since, in this scenario, communication infrastructure is experiencing problem and there is no longer any communication possible between the agents the algorithm can not converge. The control algorithm is unable to support the voltage when a lower limit is violated, until, eventually its gets better.

Wireless Communication Technology

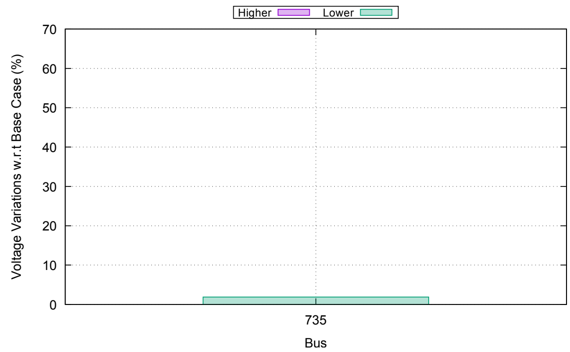
Wireless communication technology is an import technology and is considered a strong candidate for the Smart Grid deployment due to its relatively low infrastructure requirements. A model of a communication infrastructure with IEEE 802.11g is modeled and co-simulated in the proposed co-simulation environment for the performance evaluation of the distributed control algorithm and its effects on the underlying power system. The results are shows in Figure 7.16. Although, algorithm's convergence time in this case is 79 *sec*, the bus experiences an under voltage situation for almost 2 *minutes* (Figure 7.16b). After this, the controller provides the required voltage support and the voltage is regulated (Figure 7.16a).



(a) Voltage profile over time for the selected bus.



(b) Voltage limits violations on the selected bus.



(c) Percentage of voltage variations w.r.t the Best Case on the selected bus.

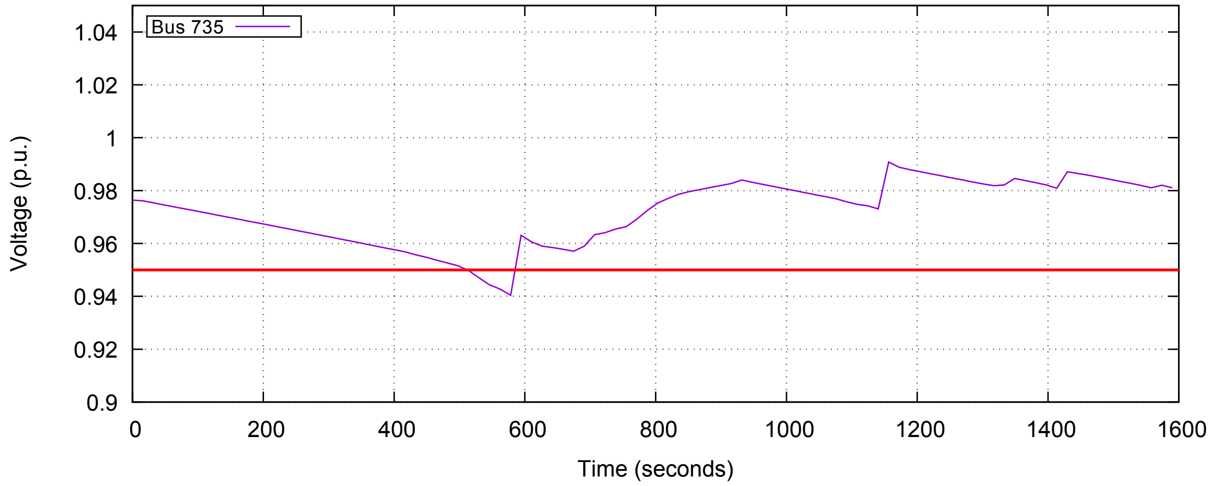
Figure 7.14: Results for communication infrastructure model with Wired 40 *Gbps*. The distributed control algorithm's is able to support voltage after a small convergence time of 32 *sec*.

Powerline Communication Technology

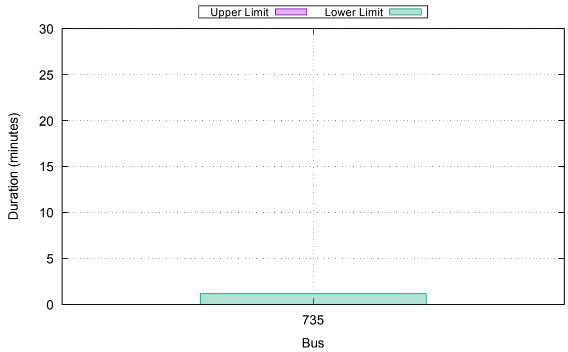
Powerline Communication (PLC) technology are among the ideal candidates for implementing communication infrastructure for Smart Grid application due to their prime advantage of using the existing electrical network infrastructure. PLC has two main categories; Broadband PLC and Narrowband PLC. Two variants of PLC are modeled for communication infrastructure. The first model used a Broadband PLC with 1 $Mbps$ while the second model is with 128 *kbps* Narrowband PLC. The results from both the scenarios are presented in Figure 7.17 and 7.18 respectively.

7.7.4 Communication Infrastructure Sharing

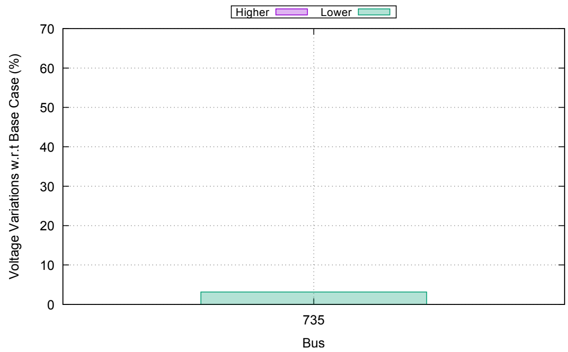
In the future, many applications/services may be using the same communication infrastructure as it may not be feasible to use a dedicated communication infrastructure for every other deployed application/service in the same or neighboring network. A communication channel scenario is model with the base network having a wired communication technology with a bandwidth of



(a) Voltage profile over time for the selected bus.



(b) Voltage limits violations on the selected bus.

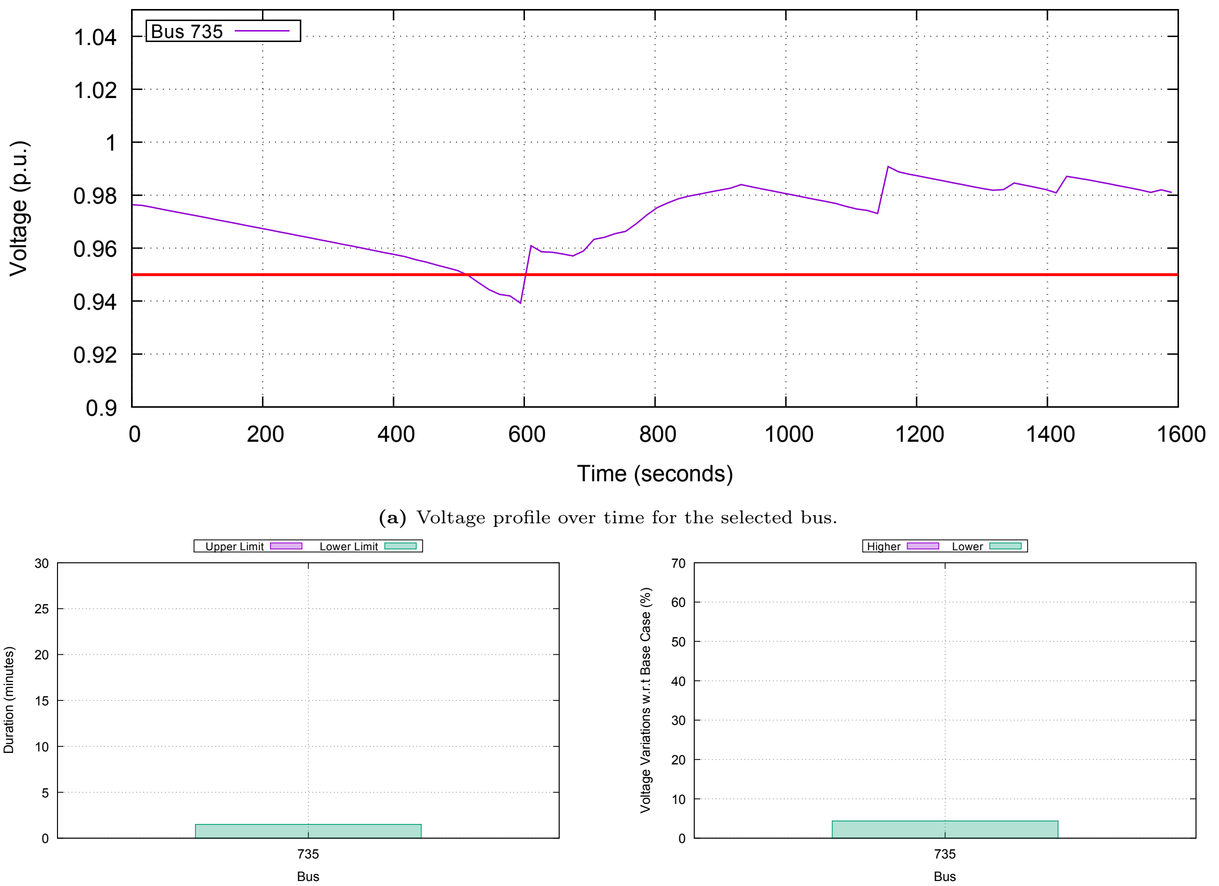


(c) Percentage of voltage variations w.r.t the Best Case on the selected Bus.

Figure 7.15: Results for communication infrastructure model with Wired 1 *Gbps*. The distributed control algorithm is able to support voltage after a small convergence time of about 57 *sec*.

1 *Gbps* with Ethernet as the link layer, TCP and IP as network and transport protocols. A constant 10 *Mbps* SCADA traffic is modeled to be passing through the same network that is being used by the agents for coordination.

Figure 7.19 shows the results of co-simulation with this model. As the results indicate, the control algorithm using this communication infrastructure scenario was unable to provide the required voltage support timely. This can be seen with a relatively large algorithm's convergence time of 294 *sec* a little higher than the PLC Broadband. The duration of over voltage is, thus, maximum.

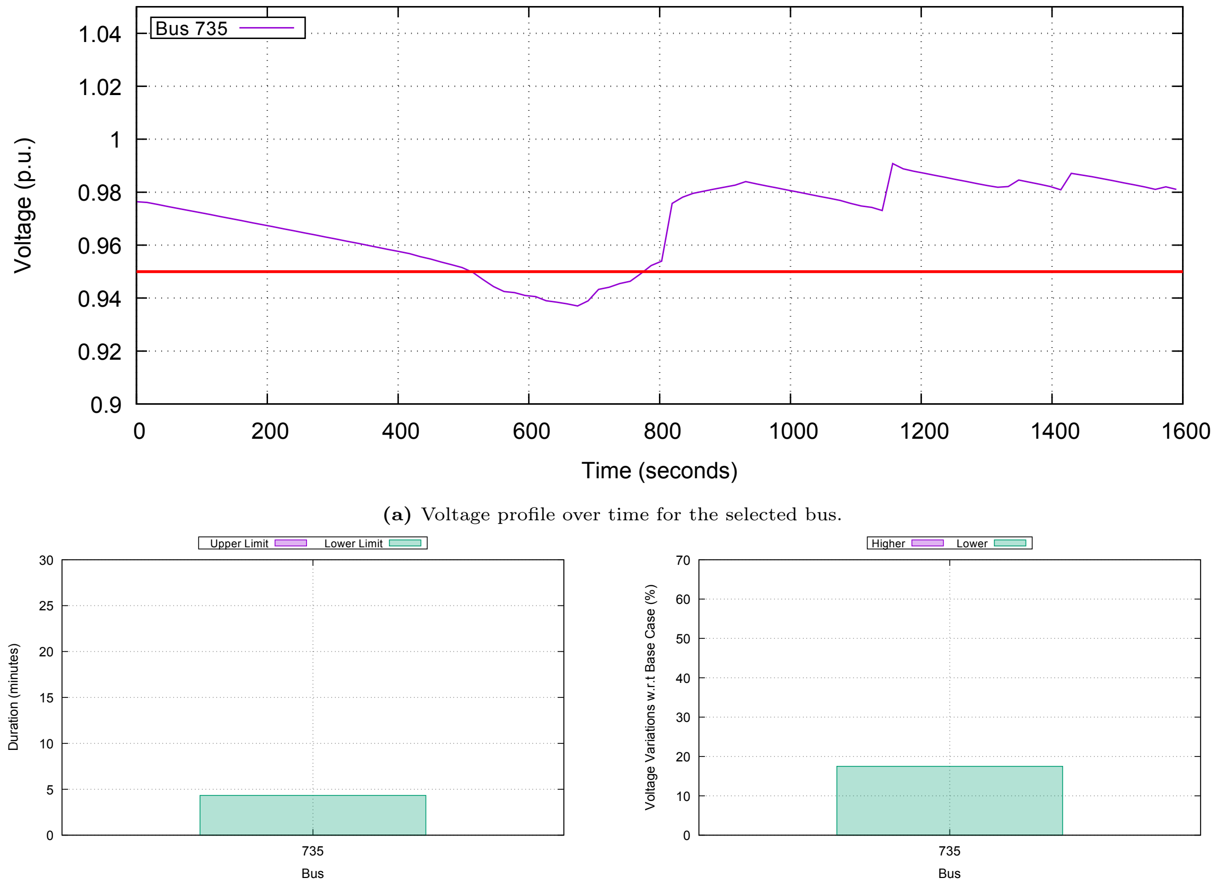


(a) Voltage profile over time for the selected bus.

(b) Voltage limits violations on the selected bus.

(c) Percentage of voltage variations w.r.t the Best Case on the selected Bus.

Figure 7.16: Results of communication infrastructure modeled with an IEEE 802.11g (Wireless 54 *Mbps*) wireless communication technology. The control algorithm is able to regulate the voltage after a delay of about 2 *minutes*.

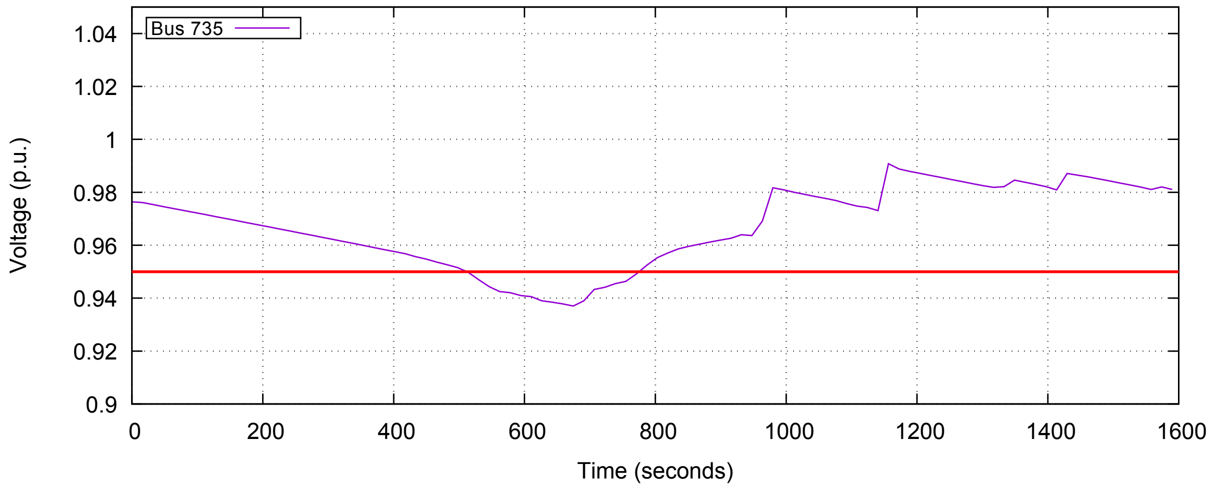


(a) Voltage profile over time for the selected bus.

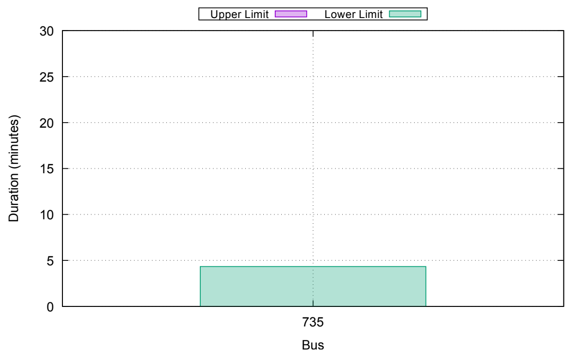
(b) Voltage limits violations on the selected bus.

(c) Percentage of voltage variations w.r.t the Best Case on the selected Bus.

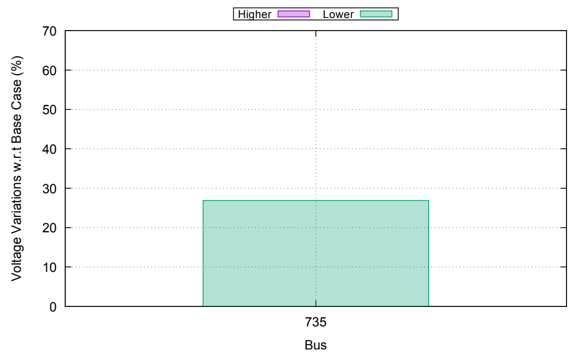
Figure 7.17: Results when communication infrastructure is modeled as a PLC 1 *Mbps* using the Powerline communication. Voltage profile and calculated KPIs are presented. Due to large convergence times, the control algorithm is not able to support the voltage timely.



(a) Voltage profile over time for the selected bus.

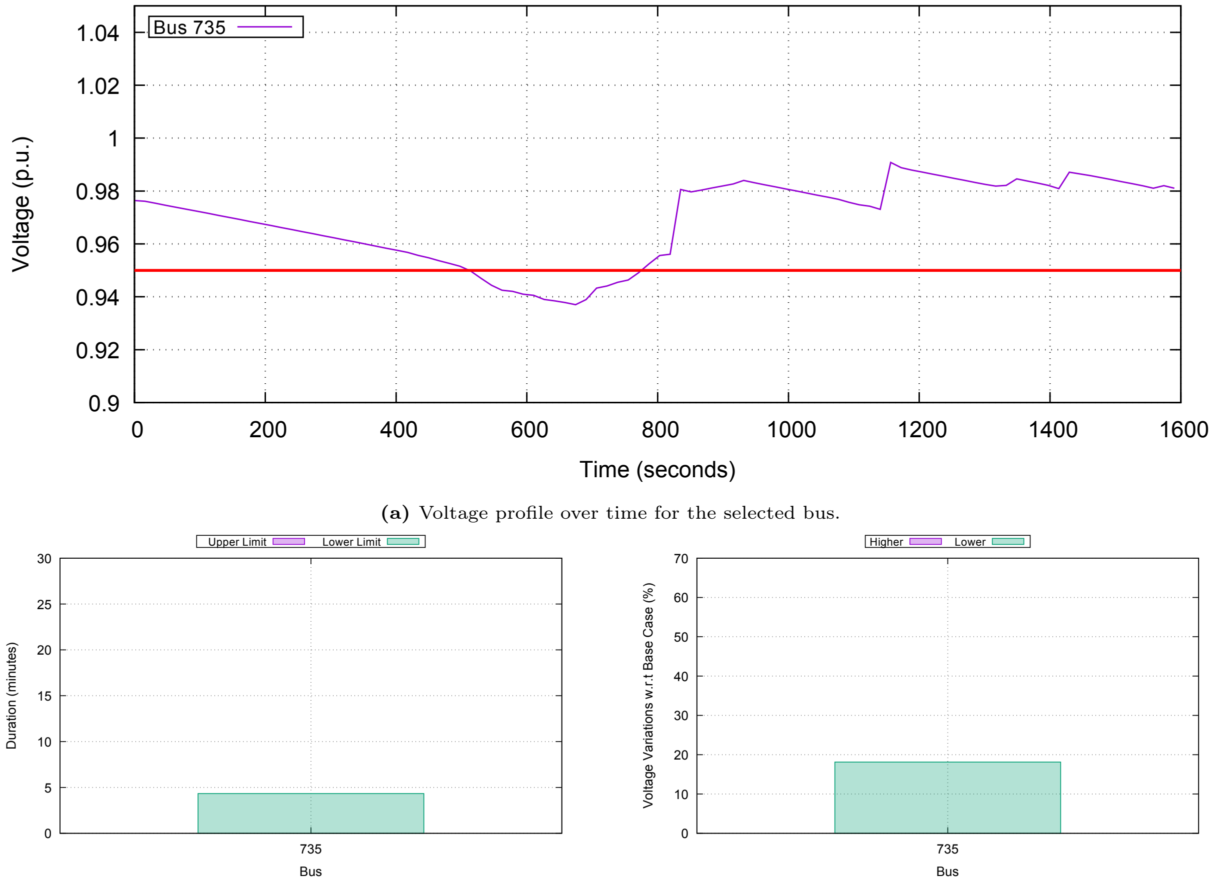


(b) Voltage limits violations on the selected bus.



(c) Percentage of voltage variations w.r.t Best Case on the Bus.

Figure 7.18: Results when communication infrastructure is modeled as a PLC 128 *kbps* using the Powerline communication. Voltage profile and calculated KPIs are presented. Due to large convergence times, the control algorithm is not able to support the voltage timely.



(a) Voltage profile over time for the selected bus.

(b) Voltage limits violations on the selected bus.

(c) Percentage of voltage variations w.r.t Ideal case on the Bus.

Figure 7.19: Results for communication infrastructure using Wired 1 *Gbps* when the network is being shared with other services having an intensity of 10 *Mbps*.

7.8 Summary

This chapter has presented the third and last case study to show the effectiveness and applicability of the proposed tool-set. A Smart Grid application to address the voltage regulation problem using a distributed control algorithm in a medium voltage distribution network is presented in this case study. The consensus based control algorithm is implemented as multi-agents system where each agent represents a distributed energy resource. In the algorithm, the agents communicate with each other whenever a voltage limit violation is detected to solve the problem making it highly dependent on communication infrastructure performance. Various communication infrastructure model with popular communication technologies and scenarios are simulated to measure performance and effects, on the system. The power system model of a modified IEEE 37-bus Feeder system is modeled with DIgSILENT PowerFactory and simulated using a Python script. The control algorithm is implemented and simulated with JADE, while communication infrastructure models are developed and simulated with OMNeT++. For co-simulation of selected simulators (power system, Python, JADE and OMNeT++) custom interfaces are developed that use TCP sockets for intra-simulator communication. A description of results along with graphs showing voltage profile and calculated KPIs are presented.

8 Results and Discussions

After presenting the adopted methodology in Chapter 4 and the tool-set along with three case studies in the Chapter 5, 6 and 7 respectively, this chapter provides a discussion on the results and answers the posed research questions. At first, capabilities, adaptability and usefulness of proposed tool-set is presented in Section 8.1. Next, a discussion on results from the three case studies are presented in Section 8.2 while, Section 8.3 answers the posed research questions.

8.1 Applicability and Usefulness

The proposed tool-set's applicability and usefulness has been demonstrated by three case studies presented respectively in the Chapter 5, 6 and 7. These case studies cover a wide range of the Smart Grid applications with embedded, centralized and distributed controllers, different time scales simulations of power systems and varying communication infrastructure models. Due to this wide applicability and usefulness, the tool-set has been adopted in two European research projects.

8.1.1 Capabilities of the tool-set

The proposed tool-set provides a detailed and fine-grain dynamical co-simulation capabilities for the analysis of communication infrastructure. Among the other major features, readily available are:

- use of well known, domain specific tools,
- generic coupling interfaces,
- modular design,
- extendable and flexible,
- larger coverage of the Smart Grid case studies,
- capable of hardware-in-the-loop and real-time simulations,

- support for embedded, centralized and distributed control applications,
- support for different time scales of power system dynamical simulations,
- detailed communication simulations,
- can be adapted as a whole or in parts.

Such capabilities enable:

- reuse of exiting models and know-how,
- reduction in implementation and testing efforts,
- enhanced reliability,
- improved collaboration among domain experts,
- easy adaption.

The use of exiting, well known domain specific tools enable reuse of existing tested models along with the know-how. This, not only reduces the implementation and testing efforts considerably but enhances the overall reliability of the study. A further advantage is the possibilities of enhanced collaboration and adaptability among the domain experts when each is allowed to working with tool of his/her own choice. Use of generic interfaces provides the flexibility and extendibility, and enables the possibilities of integrating other tools when required, opening up new possibilities for the adaption of the tool-set for any given problem. Although, there have been many good power, communication and control system co-simulation works (many are analyzed in Chapter 3), to the best of our knowledge, no other tool provides such capabilities and enables the simulation of the Smart Grid with such details and wide applicability. With these capabilities, the proposed tool-set meets its five requirements as identified in Section 3.4:

- R_1: Modular simulation component for power, communication, and control systems
- R_2: Support real-time and hardware-in-the-loop simulations
- R_3: Support embedded, centralized and distributed control applications
- R_4: Support various time scales for the power systems simulations
- R_5: Support diverse Smart Grid communication infrastructure models

8.1.2 Case Study Design

To demonstrate the capabilities and usefulness, three case studies are selected to be analyzed with the proposed tool-set and are presented in the Chapter 5, 6 and 7. Each of these case study is unique with a different class of control application and/or power system time scale simulation. Varying communication scenarios with communication technologies, failures and channel sharing are specified and performance is measured using KPIs. The three case studies are summarized in Table 8.1 and described in individual subsections below.

Table 8.1: The proposed tool-set with three variations, tailored for each case study.

Case Study	Control	Power System	Communication
I	Embedded (4DIAC/FORTE)	RMS (DIgSILENT PowerFactory)	Wired, wireless and PLC (OMNeT++)
II	Centralized (Python)	RMS (DIgSILENT PowerFactory)	Wired, wireless and PLC (OMNeT++)
III	Distributed (JADE)	Steady State (DIgSILENT PowerFactory/Python)	Wired, wireless and PLC (OMNeT++)

The Case Study I

In the first case study, a Smart Grid innovative solution is modeled to address the voltage control problem in low voltage residential network where large number of photovoltiac systems and electrical vehicles are hosted. An IEC 61499 based coordinated controller is observing the network through installed sensors. The sensors are sending network measurements to controller using a communication infrastructure. The same communication infrastructure is carrying the control commands calculated by controller to an on load tap changing transformer. This makes the performance of the system highly dependent on the performance of communication infrastructure. To validate the performance, varying communication scenarios with communication technologies, failures and channel sharing are investigated. Two KPIs are specified for power system performance evaluation while a single KPI is calculated from communication infrastructure models.

As part of the tool-set, a co-simulation environment was developed on the basis of concept model shown in Figure 5.4. The co-simulation environment consists of domain specific tools for power, control and communication modeling and simulations – DIgSILENT PowerFactory, 4DIAC/FORTE and OMNeT++. Due to nonavailability of native interfaces for coupling, custom interfaces are developed. The resultant co-simulation environment is able to provide communication infrastructure analysis for valuable insight into inter-dependencies between cyber and physical components. Among the major challenges was the development of interfaces and making these components work together.

The Case Study II

The second case study also addresses the voltage control problem in a low voltage distribution network, having a number of hosted photovoltiac systems. Control algorithm improves the active power curtailment scheme introducing fairness. The control algorithm is implemented as a coordinated controller that receives measurements from each photovoltiac system. These measurements are then used to calculate the control set point for photovoltiac system inverters in a way that the voltage remains under the limits in accordance with the standards such as EN 50160. The controller and photovoltiac systems are depended on communication infrastructure for sending and receiving, measurements and control set points. The dependency on the communication infrastructure is evident and requires that it should be further investigated to provide important insight on system performance with varying communication infrastructure models.

The proposed tool-set is applied for communication infrastructure analysis. KPIs for quantification of results are specified for power system and communication infrastructure. A co-simulation environment, necessary for the simulation of case study was developed with power, communication and control system, specialized software (DIgSILENT PowerFactory, OMNeT++, Python). A conceptual view of the developed co-simulation environment is depicted in Figure 6.4. Custom interfaces are developed for coupling the tools as there are no native interfaces available. An important feature of the developed interfaces is the use of standard and well-know tools and methods. This makes them modular in nature and enable the possibilities to connect many other tools. The results show that the conducted investigation and developed co-simulation environment is helpful in answering many questions.

The Case Study III

In the third case study, voltage regulation problem is addressed using a consensus based distributed algorithm. The algorithm is implemented as multi-agents system to utilize unique properties such as autonomy, adaption and cooperation of the agents. Such properties makes multi-agents system attractive for distributed application in many areas including the power systems [MDC+07a].

For this cases study, the power system model used is a modified IEEE 37-bus Feeder network while the distributed control system is implemented with autonomous agents in a multi-agents system. Each agent in the multi-agents system represents a distributed energy resources and implements an algorithm for providing voltage regulation. Every agent communicates with its neighbor for reaching to a consensus for its control set points. All intra-agent communication requires a communication infrastructure, making it important for the performance of the whole system. Communication parameters such as protocols, bandwidth, technology type, and failures etc. could therefor, impact the performance of this control algorithm and the underlying power system.

To analyze this Smart Grid application for communication infrastructure affects a tool-set is developed with multi-agents system and domain specific tools for power and communication systems (JADE, DIgSILENT PowerFactory, Python and OMNeT++). A conceptual view of the co-simulation environment is depicted in Figure 7.6. To access and quantify the impact, varying communication infrastructure models are co-simulated along with power system and control models. The results indicate that proposed tool-set is effective in providing valuable insight further leading to answers about performance, affects and design of communication infrastructure.

8.1.3 Adaption of The Tool-set

In addition to the these case studies presented in this dissertation, the tool-set has been adopted in AIT Austrian Institute of Technology [202] for two European research projects:

1. DG Demo Net - Smart LV Grid [204] and
2. SPARKS [229],

further warranting its applicability and usefulness. Some of this work is available at [SKAS14] and [FSK+16].

In DG Demo Net - Smart LV Grid [204], the tool-set is extended with the integration of additional tools such as GridLab-D, SCADA-BR, MATLAB for different use cases regarding demand response and test of control strategies in different communication infrastructure models and scenarios. Most of these co-simulation are performed with hardware-in-the-loop at AIT's Smart Grid test and integration laboratory (SmartEST Lab).

The SPARKS [229] is about the identification and prevention of cyber attacks on the Smart Grid infrastructure. Parts of the proposed tool-set has been seamlessly integrated into its exiting co-simulation environment. The generic interfaces and communication models are used to model cyber attacks and has been successful in identifying the effects and patterns [FSK+16].

8.2 Results

The proposed tool-set is used for co-simulation of three case studies to analyze the performance with varying communication infrastructure models. The communication infrastructure models include popular wired, wireless and powerline communication technologies while quantification of performance is done using the KPIs. One of the objectives of the proposed tool-set is to help in identifying the best communication infrastructure model for a specific Smart Grid solution. The answer to this question is highly application dependent and needs to be investigated. The results from the three investigated case studies are given in Figures 8.1, 8.3 and 8.5. These figures show a comparison of these KPIs after normalizing (z scores) using Equation (8.1). Additionally, percentage change in each KPIs with respect to change in communication infrastructure model are given in Figures 8.2, 8.4 and 8.6. The dotted rectangle identifies communication infrastructure models where performance of the system is very much identical and hence, there is no significant change in performance of power system by changing the communication infrastructure model. From values of power system KPIs, it can be seen that there is minimum violation and variation in voltage, providing the required performance.

$$z = \frac{x_i - \mu}{\sigma}, i = 1, \ldots, n \tag{8.1}$$

Where x_i is the KPI values in ith scenario, μ is the mean and σ is the standard deviation.

The results of individual case studies are discussed below. The discussion, further identifies the suitable communication infrastructure models for the given Smart Grid application, based on the calculated KPIs of interest, however, it is to be notices that not all identified communication infrastructure models may be suitable due to some implementation requirements, characteristics and/or constraints.

8.2.1 Analysis of Results from the Case Study I

Figure 8.1 shows a comparison of KPIs from eight communication infrastructure models, including two reference scenarios, co-simulated in the Case Study I (Chapter 5). The results overall shows a non-linear behavior. It can be seen that all three KPIs remain at the same level for wired, wireless and two variations (PLC 1 *Mbps* and PLC 128 *kbps*) of Powerline communication technologies. However, a sharp increase is very visible for narrow-band Powerline communication (PLC 33 *kbps*) technology. Such sudden decrease in performance is due to the nature and properties of Powerline communication that uses a bus topology, half-duplex communication mode and having a comparatively low bandwidth. From the results, the performance can be classified into two clusters, first consisting of two variation of wired, the wireless and two variation of Powerline technology. From these results it can be safely deduced that the minimum required communication infrastructure, providing desired performance for this case study is PLC 128 *kbps*. Below this, stepping into second cluster, will cause a consider decrease in performance.

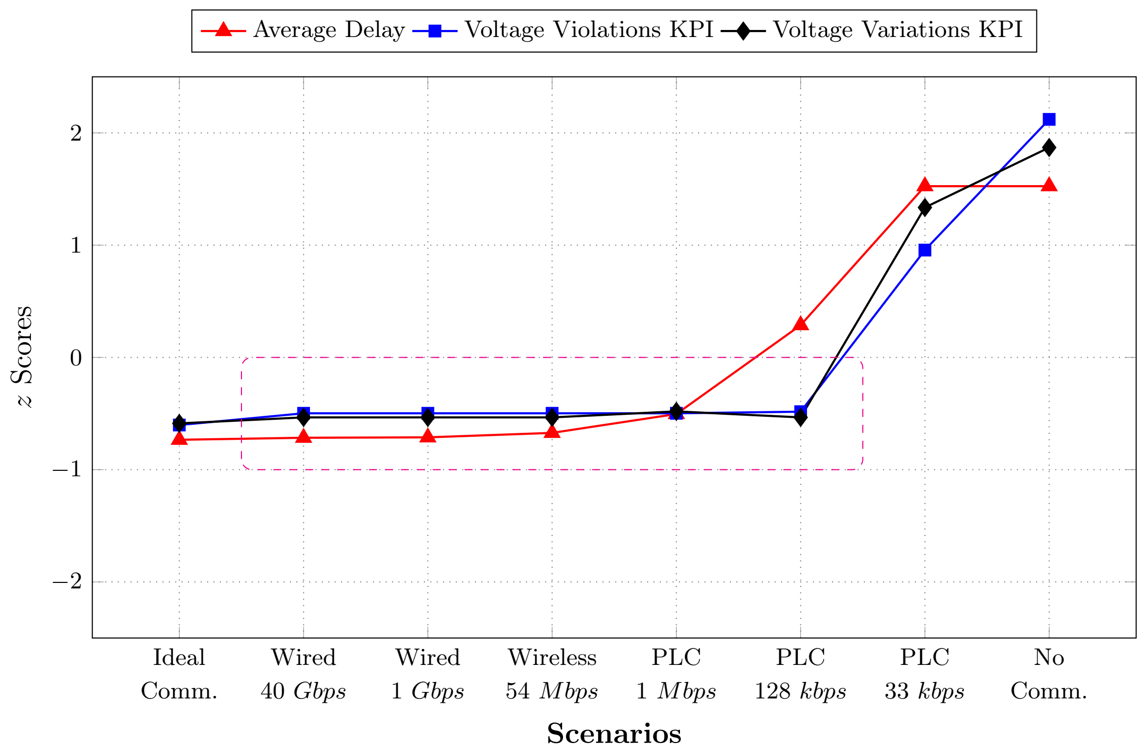


Figure 8.1: For the Case Study I: Normalized KPIs comparison from different scenarios.

Another view of the results presenting percentage change in KPIs between communication infrastructure models (lower to higher performance) is presented in Figure 8.2. There is a considerable change in all three KPIs (55, 98, 95%) when moving from PLC 33 *kbps* to PLC 128 *kbps*, while there is less change in PLC 33 *kbps* to PLC 1 *Mbps* as compared to previous (78, 15, 78%). The change in voltage violation KPI is almost negligible (1%) when moving from PLC 1 *Mbps* to Wireless 54 *Mbps*, however the change in voltage variation and average delay is there. Same prevails in the case for Wireless 54 *Mbps* to Wired 1 *Gbps* model. From Wired 1 *Gbps* to Wired 40 *Gbps*, although quite a big performance difference in communication infrastructure, has a very low impact on KPIs, also indicating a non-linear relationship between communication infrastructure model performance and Smart Grid solution's performance. From the figure, it is clear that if we are only concerned about voltage violations, PLC 1 *Mbps* can be the minimum acceptable communication infrastructure. However, if we need both voltage violation and variation KPIs to be good, then the communication infrastructure requirement will be higher.

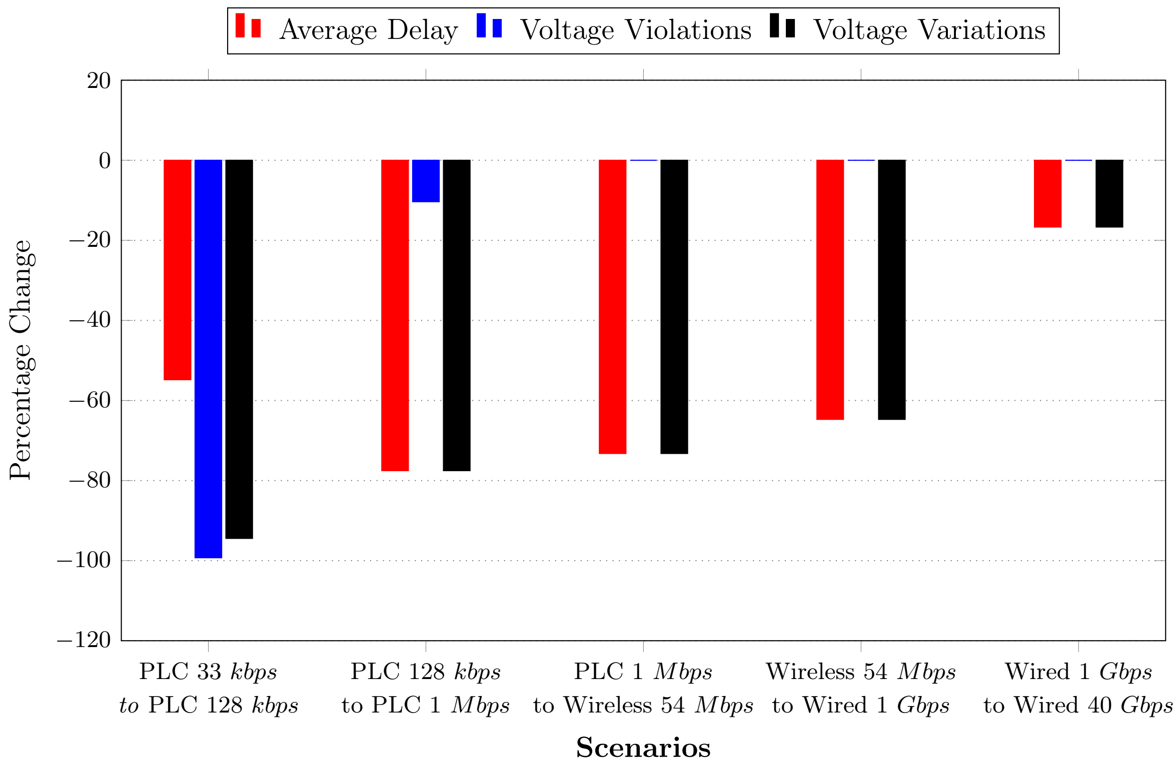


Figure 8.2: Differential KPI comparison for the Case Study I.

8.2.2 Analysis of Results from the Case Study II

For the Case Study II (Chapter 6), Figure 8.3 shows a comparison of KPIs from six modeled communication infrastructure and two reference scenarios (the Best Case and the Worst Case). In the figure, an overall non-linear relationship between the KPIs and communication infrastructure is very evident. Also, voltage violations KPI and curtailed power KPI show an inverse relationship. The reason being that control efficiency improves with the improvement of communication infrastructure model and cases a more stable system with lower voltage violations but this results in an increased curtailed power, to prevent over voltages. In the case of two variations of wire (Wired 40 *Gbps* and Wired 1 *Gbps*) and Wireless 54 *Mbps*, the values of curtailed power and voltage violations remain almost steady indicating a similar system performance. However, voltage violations start to rise for all three variation of powerline communication reaching the level of the Worst Case with PLC 33 *kbps*. For performance, simulated communication infrastructure models can be classified into three clusters, first consisting of Wired 40 *Gbps* and Wired 1 *Gbps*, second consisting of Wireless 54 *Mbps* and PLC 1 *Mbps*, while third cluster consist of PLC 128 *kbps* and PLC 33 *kbps*. The middle cluster represents the communication infrastructure where KPIs are not extreme. From this cluster, PLC 1 *Mbps* is thus the minimum in terms of KPI performance. Again it is to be noted that not all identified communication infrastructure models may be suitable due to some implementation requirements, characteristics and/or constraints.

Figure 8.4 shows percentage change in individual KPIs achieved when moving towards higher performance communication infrastructure models. A huge (up to 345%) change in curtailed power is visible about moving from PLC 33 *kbps* to PLC 128 *kbps*. Although, less than the previous case, but considerably significant (244%, 61%) change can be observer between the curtailed power and voltage violations KPIs calculated during the simulation of communication infrastructure from PLC 128 *kbps* to PLC 1 *Mbps*. Curtailed power KPI has changed little (19%) but there is a significant change (95%) in voltage violations KPI between PLC 1 *Mbps* and Wireless 54 *Mbps* indicating that 95% voltage variations can be reduced if communication infrastructure model Wireless 54 *Mbps* is used instead of PLC 1 *Mbps*. There is a negligible change (1%) in calculated curtailed power between Wireless 54 *Mbps* to Wired 1 *Gbps* while a 62% reduction in voltage violations can be seen. No significant performance improvement can be witnessed by replacing the communication infrastructure with Wired 40 *Gbps* from Wired 1 *Gbps*. From these results it can be concluded that percentage change in KPIs is significantly higher between communication infrastructure models in third cluster (PLC 33 *kbps* and PLC 128 *kbps*) while such difference is not extreme for second and first clusters.

8.2.3 Analysis of Results from the Case Study III

Similarly, Figure 8.5, shows a comparison of calculated KPIs for six communication infrastructure models and a reference model, for the Case Study III (Chapter 7). The Worst Case scenario, reports an infinite time, as voltage control algorithm do not converge in the absence of communication, and is omitted from the comparison. Although, the performance is affected by communication infrastructure model used but the relationship is not linear. All three calculated KPIs in the case of Wired 40 *Gbps*, Wired 1 *Gbps* and Wireless 54 *Mbps*, show very similar performance. However, the performance starts to decrease considerably for all three variations of powerline communication infrastructure models. All three KPIs show somewhat different behavior. Voltage variation, after increasing considerably in the case of PLC 1 *Mbps* becomes steady

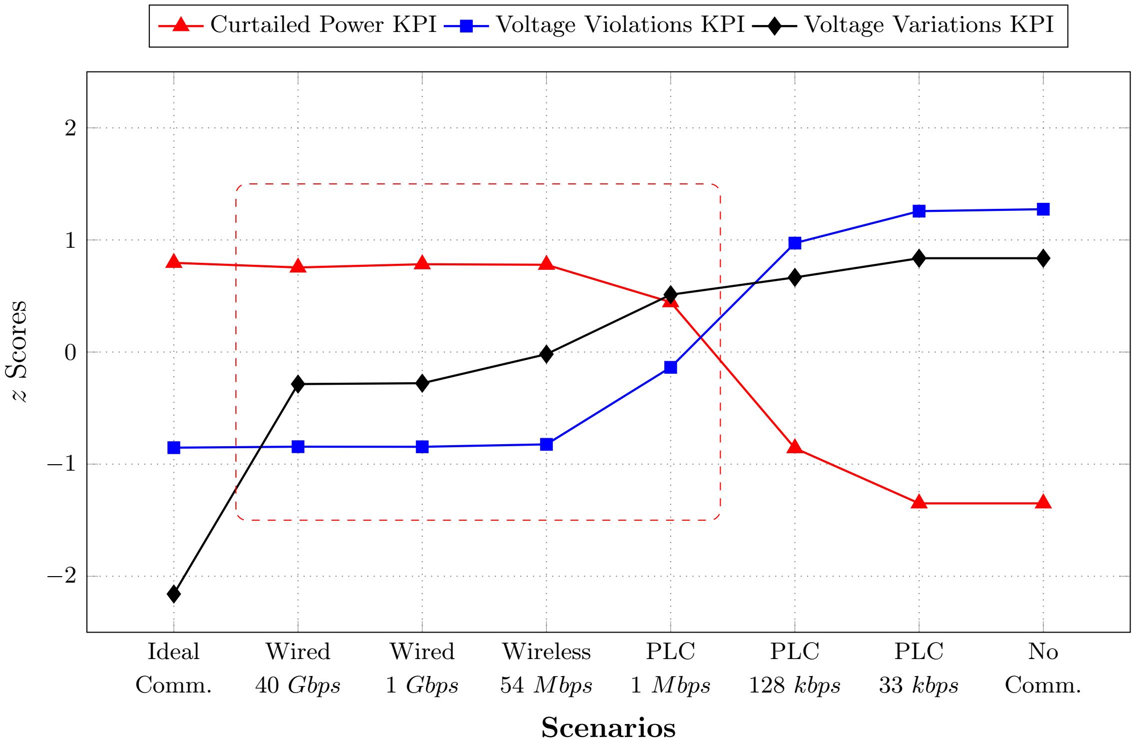


Figure 8.3: For the Case Study II: Normalized KPIs comparison from different scenarios.

for the other two variations (PLC 128 *kbps* and PLC 33 *kbps*). This behavior is specific to this case study where the control action is delayed enough and the voltage stabilize again before it. Voltage variations and convergence time, however, show a near linear behavior for all variations of powerline communication technologies.

Clearly, the communication infrastructure models, based on calculated KPIs, can be classified into two clusters – Wired 40 *Gbps*, Wired 1 *Gbps* and Wireless 54 *Mbps* being similar in performance in first cluster, while all three variations of powerline communication technologies (PLC 1 *Mbps*, PLC 128 *kbps* and PLC 33 *kbps*) falling in the second. From this classification, minimum requirements can be identified when the performance remains good. This minimum thus is Wireless 54 *Mbps*, moving below which the performance degrades considerably.

Similar to other two case studies, Figure 8.6 shows a relative percentage change in KPIs between the two communication infrastructure models, for this case study. There is no change (0%) in voltage violations when moving from PLC 33 *kbps* to PLC 128 *kbps* for the reason stated above, however, a considerable decrease (57%) is algorithm convergence time along with a decrease of 23% in voltage variations can be seen. Again, there is no change in voltage violations but a considerable decrease (32% and 34%) both in algorithm convergence time and voltage variations exists when communication infrastructure model of PLC 128 *kbps* is replaced with PLC 1 *Mbps*. Perhaps, the biggest performance difference can be seen when moving from PLC 1 *Mbps* to Wireless 54 *Mbps* with all three KPIs showing a considerable performance improvements. The convergence time

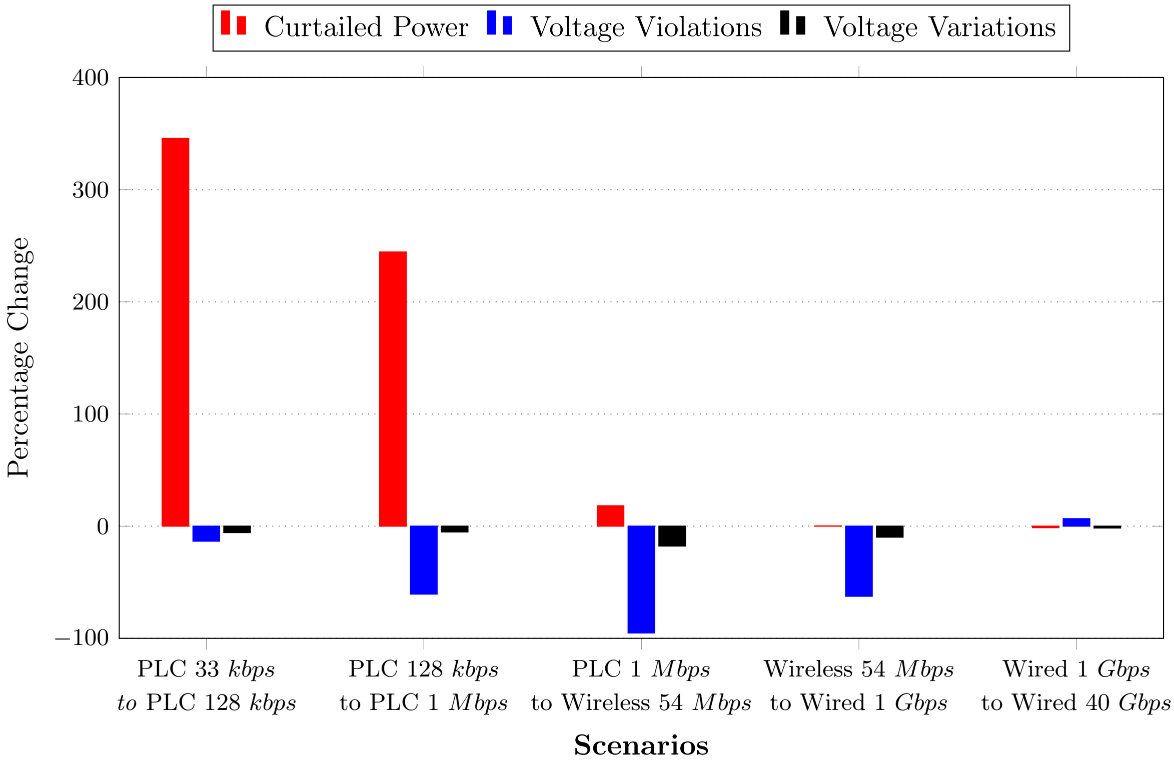


Figure 8.4: Differential KPI comparison for the Case Study II.

decreased by 73%, voltage violations decreased by 65% and voltage variations are decreased up to 75%. This also signifies the change of performance cluster and identifying the minimum communication infrastructure model for achieving required performance. A further relative performance gain up to 25% can be achieved with Wired 1 *Gbps* from Wireless 54 *Mbps* and another 40% when using Wired 40 *Gbps* as communication infrastructure model from Wired 1 *Gbps*.

8.3 Research Questions

The research questions, posed in Section 1.2, can now be answered positively, and are presented below. Two intermediate questions, regarding identification of the suitable method and the architecture for the Smart Grid analysis, are answered first followed by the main question.

8.3.1 Identification of Suitable Method

The statement of this question is shown in Figure 8.7, asking for the identification of the Smart Grid modeling and simulation methods that can be utilized by many domain experts involved in its design and analysis, and has less implementation efforts as compared to others methods. It further asks for analyzing the effectiveness of the co-simulation method.

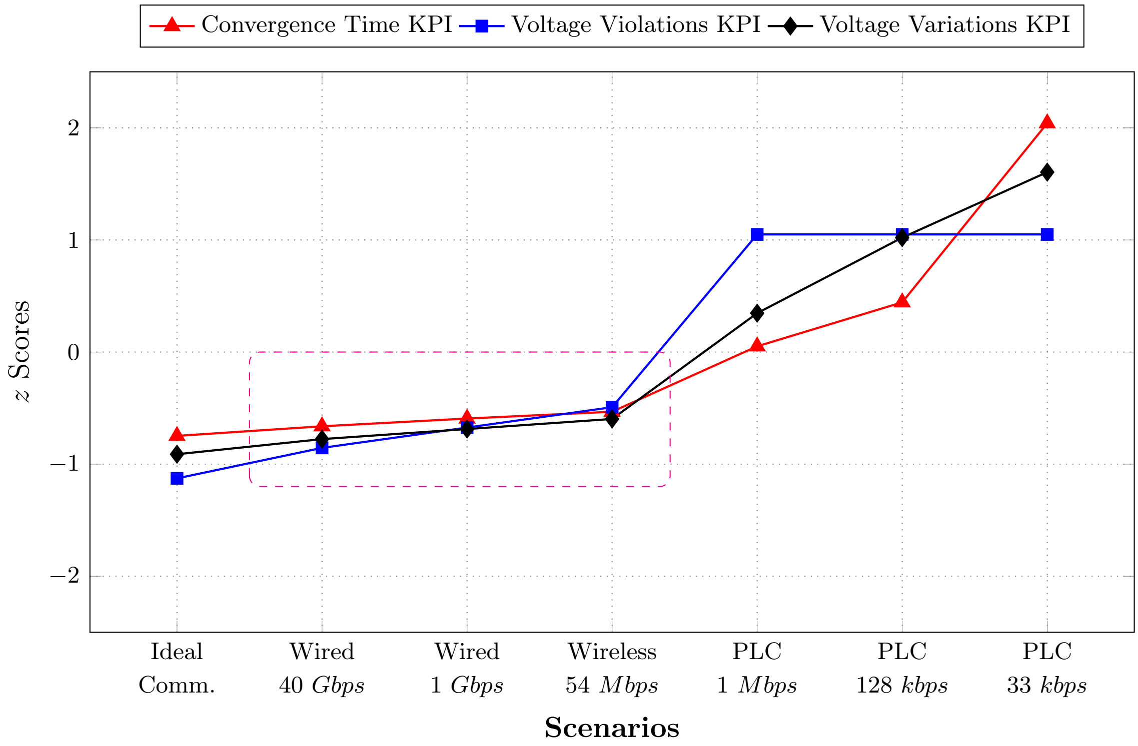


Figure 8.5: For the Case Study III: Normalized KPIs comparison from different scenarios.

Motivated by many technological, environmental and political factors, the ongoing modernization of power system is set forth by the vision of *Smart Grid*. The Smart Grid has been aiming for a power system that is more situation aware, automated, economic, resilient, reliable, and environment friendly. To achieve these aims, it integrates information and communication technology, and the modern hardware into the power systems to enable advanced two-way communication, enhanced automation, monitoring and control, self healing capabilities, and increased hosting of renewable energy resources. With this tight integration of computation and communication into power systems, the Smart Grid has become a large Cyber Physical System, with complex *cyber* and *physical*, *inter* and *intra* domain, interactions and interdependencies. Due to uniqueness of these systems, traditional methods/tools are no longer appropriate. The analytic methods are far from suitable since the interdependencies and interactions are too complex to be represented in a mathematical model, when the relationship can not be represented.

The other viable option would then be to use simulation based methods. For the Smart Grid, being a multi-domain system, it is no longer possible to model the participating domains independently and thus a multi-domain modeling and simulation approach is required to be applied. Among the possible multi-domain modeling and simulation options [FG88] are:

1. Represent the whole system as one big monolithic model that can be simulated.
2. Modeling and simulating each domain sequentially, incorporating the identified effect into

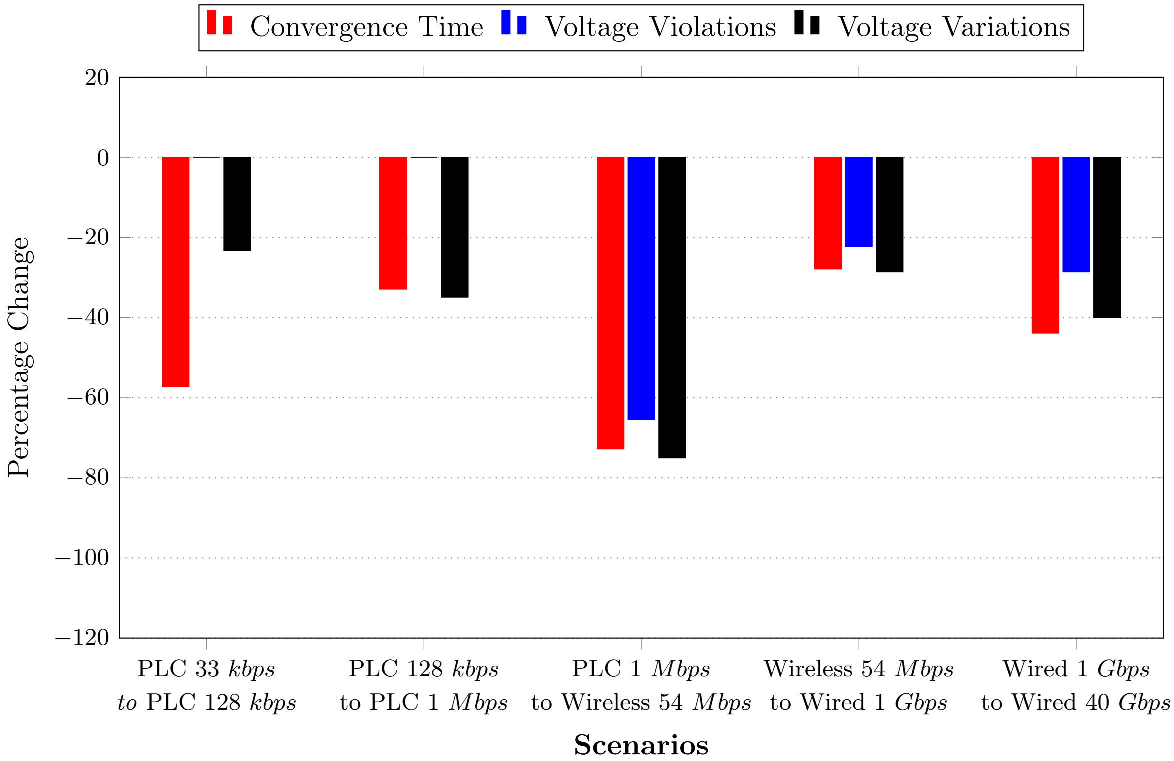


Figure 8.6: Differential KPI comparison for the Case Study III.

What methods exists for analyzing this influence? How effective is the co-simulation based methodology in terms of:

1. implementation efforts,
2. suitability for inter-disciplinary modeling, for domain experts from power system, controls, and communication?

Figure 8.7: Intermediate Question 1 (Section 1.2).

others.

3. Couple exiting well know and domain specific tools to form a hybrid modeling and simulation.

The first option represents a monolithic approach (Figure 8.8) and requires development of a new integrated simulator that could simulate all aspects of a Smart Grid – power system, communication, and control. Since, providing the level of abstraction, details in modeling and sophistication as is usually available in a domain specific tools is not easily achievable, it is not a feasible option.

The software could take years and thousands of men hours to attain a reasonable representations and simulation. Furthermore, learning a new software and/or language by every domain expert involved, just for the sake of integration may not be a viable option [LFS+14]. Monolithic approach also requires a system specification language/method that could support all the Smart Grid domains at different level of abstraction but such a universal language is far from reality [HLMV+99].

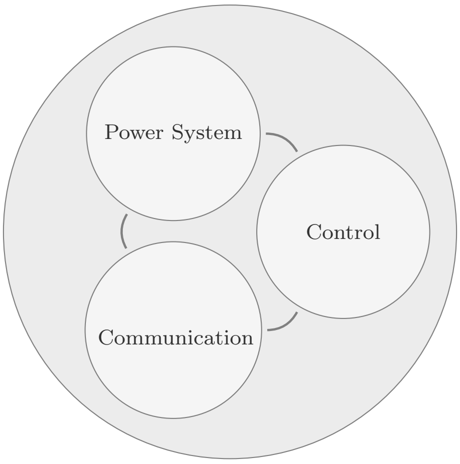


Figure 8.8: Monolithic approach. Represent the whole system as one big monolithic model that can be, then, simulated.

The second option, although looks attractive and somewhat simple, do not capture the interaction and interdependencies, and may only be suitable for very limited scenarios [Lin12]. One possible implementation, as shown in Figure 8.9, for a Smart Grid communication infrastructure analysis according to this approach, would be to first study the communication infrastructure and extract communication behavior and incorporate it into control system simulation and identify the effects. Then, incorporate control behavior and effects into power system simulation to see the effects of communication infrastructure on power system.

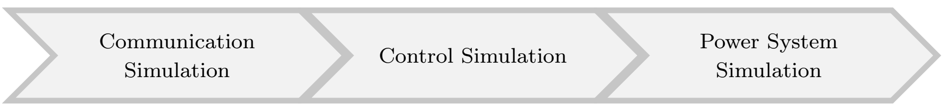


Figure 8.9: Example implementation in accordance with second option.

The third option is the co-simulation (Figure 8.10) – combining individual domain-specific simulators in a loosely coupled fashion and simulate them in a coordinated way where participating simulators may not be working with the same modeling paradigm – providing maximum flexibility with minimum implementation efforts. With co-simulation, different Smart Grid domain experts can use their own specialized domain specific tools for modeling and simulation, and can avoid learning a new tool just for integrating models. This saves both the time and cost as, using co-simulation results in re-use of existing models, libraries and expertise. Co-simulation is, thus, considered to be one of the important method for solving multi-domain problems [LFS+14, PWSE14].

Co-simulation can be achieved in two different approaches. In the first approach, although not popular and provide limited modeling and simulation capabilities, one of the individual domain specific simulation tool is extended to provide the support for the other domains. While, in the second, considered to be a more flexible approach, independent simulator for individual domains are combined through co-simulation interfaces to provide a simulation of the Smart Grid. However, providing such co-simulation is not a trivial task as it may requires to co-ordination between heterogeneous sub-systems and adaption to time-varying *cyber* and *physical* contexts [LFS+14, Tri15].

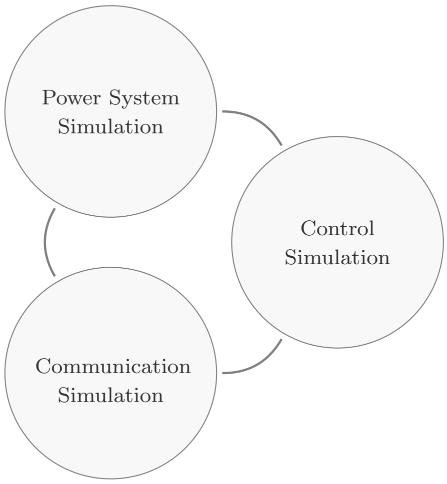


Figure 8.10: The Smart Grid analysis using the co-simulation approach. Individual, existing domain-specific simulators are combined in a loosely coupled fashion. The participating simulators are not required to be following the same modeling paradigm.

A co-simulation-based study requires extra implementation efforts. The efforts are mainly for development of interfaces needed for coupling the individual simulators together. However, this is a one time effort and can be reused. In terms of benefits, the approach provides maximum flexibility with minimum implementation efforts. The co-simulation setup can be readily used for simulating multiple scenarios, once the simulators are coupled according to needs.

The Smart Grid is a multi-domain system and there are many domain experts involved in designing and developing it. These experts are using different tools for modeling their sub-system. Since, in co-simulation it is not necessary that all participating tools be following same modeling paradigm, making it more suitable when different domain experts are involved, with different expertises and tools.

It can, therefore, be concluded that co-simulation is a better methods for the Smart Grid analysis among the available options.

8.3.2 Co-simulation Design for Communication Infrastructure Analysis

Based on literature analysis, presented in Chapter 3, and the discussion in Section 8.3.1, it can be concluded that, co-simulation is an effective method of communication infrastructure analysis in the Smart Grid. The next question, presented in Figure 8.11, is regarding an extendable co-simulation design that could support divers Smart Grid case study analysis.

> What is an extendable co-simulation design to enable versatile communication case study for range of Smart Grid applications with different tools and interfaces?

Figure 8.11: Intermediate Question 2 as presented in Section 1.2.

The Smart Grid is a large and divers system and it is not possible to design everything in advance. Extendability is, thus, an important design principle that makes it possible to tailor the developed tool-set according to needs, either by introducing new feature or by altering existing. To achieve an extendable design, following are the identified requirements:

- Modular design,
- generic interfaces,
- use of well know technologies and tools, and
- necessary level of abstraction.

These requirements are addressed in the developed tool-set for communication infrastructure analysis, in this dissertation. Modular design enabled the tool-set to be used as whole are in parts. Generic interfaces, along with use of well know technologies and necessary level of abstraction has helped in achieving the extendability, further enhancing adaptability and flexibility. Such is evident with the presented case studies and tool-set's adaptability in European research projects.

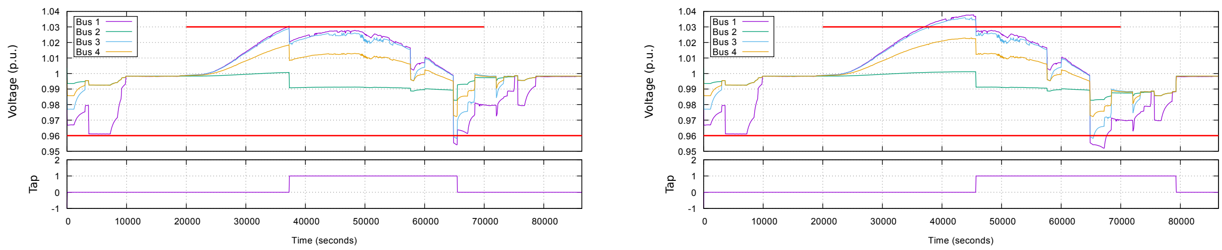
8.3.3 Smart Grid Performance Dependency on Communication Infrastructure

The results obtained from application of the proposed tool-set on three case studies can be used to answer this question. Figures 8.13, 8.14 and 8.15, each shows two results from the three case studies. Each result represents a different scenario analyzed with the proposed tool-set. From these results the effects of communication infrastructure parameter changes can be seen on the underlying power systems.

For the Case Study I, Figure 8.13a shows that the voltage is regulated when communication infrastructure is modeled with a wired communication technology having 1 *Gbps* bandwidth but, there are voltage limit violations for PLC 33 *kbps* as can be seen in Figure 8.13b.

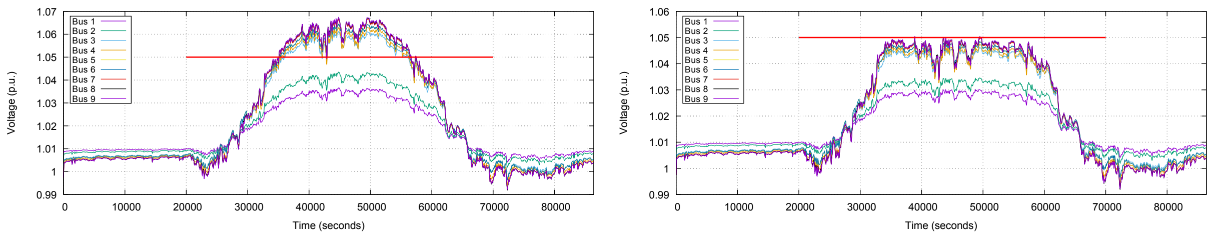
How do communication parameters affect Smart Grid performance and what indicators could be used to measure this?

Figure 8.12: Research Question (Section 1.2)



(a) Wired 1 *Gbps* **(b)** PLC 33 *kbps*

Figure 8.13: Subset of results from the Case Study I.

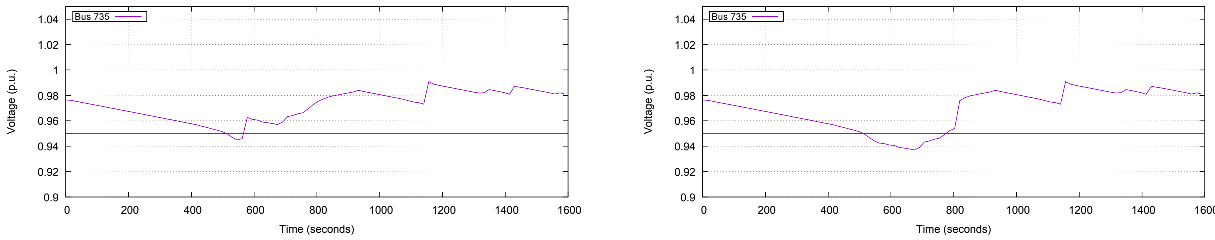


(a) Communication Failure. **(b)** Wired 1 *Gbps*

Figure 8.14: Subset of results from the Case Study II.

Similarly, for the Case Study II, Figure 8.14a shows large over-voltages when controller is not functional due to communication failures while Figure 8.14b shows that the control scheme is effective when communication infrastructure model is a Wired 1 *Gbps*.

In Figure 8.15a and Figure 8.15b, the difference in Smart Grid performance when communication infrastructure is modeled with Wired 40 *Gbps* and PLC 1 *Mbps*, respectively, for the Case Study III.



(a) Wired 40 *Gbps* **(b)** PLC 1 *Mbps* (Broadband PLC)

Figure 8.15: Subset of results from the Case Study III.

The tool-set can further be used to investigate and answerer related questions such as:

1. What communication infrastructure would be suitable for a specific Smart Grid solution? How can its performance be evaluated under different conditions?
2. To what degree a communication infrastructure is able to satisfy the requirements of a certain Smart Grid application?
3. How communication characteristics and/or parameters such as e.g. bandwidth, protocols, latency, failures, cyber attacks etc. could affect the monitoring and control operations in Smart Grid?

9 Conclusion

There is an ongoing transformation of traditional power system into *Smart Grid*. This vision of Smart Grid is the modernization of power system and is driven by the fact that a more intelligent, reliable, efficient, economic and environment friendly power system could result in by a tight integration of information and communication infrastructure (*cyber*) into the power system (*physical*). The communication infrastructure could provide advanced two-way communication enabling real-time monitoring and control, increased automation and self-healing capabilities. With these capabilities, the Smart Grid further enables massive and efficient hosting of distributed energy resources and storage, provides sustainable power delivery with efficiency, enables distributed nature of network management, improved asset efficiency and utilization, and supports electrification of transportation systems [GWP+14, CSF+16, FK15]. The communication infrastructure is nervous system of the Smart Grid and thus, is crucial for the Smart Grid realization. It is therefore, a necessary requirement to develop inter-operable communication infrastructure that not only connect divers equipment and devices but fulfills the requirements of the Smart Grid applications and services. This mandates that such methods and tools be identified that are capable of providing insight into the tight integration of *cyber* and *physical*. Due to non-availability of appropriate models and tools, modeling, simulating, analyzing and designing an eligible communication infrastructure would meet many new challenges.

9.1 Summary of the Work

The problem of communication infrastructure analysis for Smart Grid is addressed in this work. The Smart Grid, being a Cyber Physical System, is composed of multiple interacting domains having complex inter and intra-domain interactions and interdependencies as depicted in Figure 1.3. Due to these interdependencies and interactions, a multi-domain modeling and simulation approaches are needed as it is no longer possible to model participating domains independently. In Chapter 3, the co-simulation is identified as the preferred approach for the Smart Grid modeling and simulation due to its many advantages including unprecedented coverage of multiple domains, without sacrificing the details. The chapter further provides a detailed analysis of the literature regarding modeling and simulation of the Smart Grid, and identifies requirements for a co-simulation based tool-set for the Smart Grid communication infrastructure analysis. A simplified view of the three mains steps in the applied methodology, presented in Chapter 4, for the analysis is depicted in Figure 9.1. In first step, power and control systems are modeled in the domain specific tools along with communication infrastructure scenarios and key performance indicators. In the second step, a communication model is generated for each communication scenario. These communication scenarios are then used along with power and control system models and the key performance indicators to make a simulation scenario. The simulation scenarios are then co-simulated with tool-set. The collected results are analyzed to calculated KPIs, in the last step.

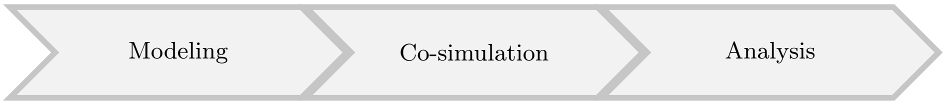


Figure 9.1: Simplified view of major steps in adopted analysis methodology.

Three case studies are selected to be analyzed and are presented in the Chapter 5, 6 and 7. Each of the case study is unique with a different class of control application and power system time scale. Although, Smart Grid is transforming power system at all levels, there is, presently, sparse control available at distribution grid level [MOD14]. This enabling a large range of possible Smart Grid application and case studies are focused mainly at low voltage and medium voltage distribution levels.

In the first case study, presented in Chapter 5, a Smart Grid innovative solution is modeled to address the voltage regulation problem in low voltage residential network where large number of photovoltiac systems and electrical vehicles are hosted. An IEC 61499 based coordinated controller is used to observe the network through installed sensors. These sensors are sending measurements to controller using a communication infrastructure. The same communication infrastructure is carrying the control commands, calculated by controller, to on load tap changing transformer. This indicates a high dependency of control system over communication infrastructure.

The second case study, presented in Chapter 6, also addresses the voltage control problem in a low voltage distribution network, having a number of hosted photovoltiac systems. Control algorithm improves the active power curtailment scheme, enhancing fairness. The control algorithm is implemented as a centralized coordinated controller receiving measurements from photovoltiac systems feeding in the system. These measurements are then used to calculate the control set points for individual photovoltiac systems, in a way that the voltage remains under the limits, in accordance with the standards like EN 50160. The controller and photovoltiac systems are depended on communication infrastructure for sending and receiving, measurements and control set points.

While, in the third case study, presented in Chapter 7, a Smart Grid solution with a distributed consensus-based algorithm used for voltage regulation in a medium voltage distribution network, is analyzed. The underlying power system model is a modified IEEE 37-bus Feeder network while the control system is implemented with autonomous agents in a multi-agents system. Each agent in the multi-agents system represents a distributed energy resources and implements an algorithm for providing voltage regulation. Every agent communicates with its neighbor for reaching to a consensus for its control set point. Agent communication requires a communication infrastructure, making it significant for the performance of whole system.

To address these divers case studies, three variations of tool-set are implemented. Each variation is tailed to a specific class of control application and power system time scale. Varying communication infrastructure models and scenarios with popular wired, wireless and PLC technologies are analyzed for each case study and results are quantified using KPIs.

9.2 Findings and Contributions

Among the major contributions of this work is the co-simulation based tool-set for proving fine-grained and detailed simulation of power system, communication and control domains of Smart Grid. The use of well-known, domain specific tools, in a modular design with generic interfaces makes the tool-set highly extendable and flexible. Such features ease in adaptability and enhances usability. The tool-set enables analysis of divers Smart Grid case studies consisting of embedded, centralized and distributed control applications, steady state and RMS time scale simulations of power system and communication infrastructure modeling with popular wired, wireless and Powerline communication technologies.

For the three case studies, tool-set provided the detailed analysis in identifying minimum and optimal communication infrastructure models meeting the required performance requirements. Important insight was provided in the performance and behavior of system when communication failures and communication infrastructure sharing scenarios are analyzed. These finding are highly application dependent and can not be generalized, however, the relationship between communication infrastructure and Smart Grid performance are found to be non-linear in every case.

9.3 Outlook and Future Work

The need for Smart Grid simulation is fairly evident and is a flourishing research field because of the increasing number of ICT and control integration in power system. Such growth is motivated by the need of an increase monitoring and control for better situation awareness, compensation for aging infrastructure, self-healing capabilities and for seamless integration of distributed energy resources, to name some. Furthermore, economy motivated controls are at the rise in energy markets. The task of designing, validating and deploying such applications is becoming more and more complex. There is a strong need for tools, like the one presented in this dissertation, to provide support in these activities. Simulator coupling with real hardware (hardware-in-the-loop) provides seamless system integration capabilities as there is no need to change the interfaces when deploying.

The developed tool-set can only be used for small to medium sized simulation. However, its scalability can be improved incorporating a middleware that could over come some constraints in the developed interfaces and could share some responsibilities. Another, future work is the inclusion of simulation correctness measure by estimating the error introduced in co-simulation.

Appendices

A Communication Infrastructure Models and Scenarios

A.1 The Case Study I

Table A.1: A subset of the Case Study III communication infrastructure models and Scenarios.

Category	Name	Description	Model
Technology	Wired	Two variations of wired communication technology (Wired 40 *Gbps* and Wired 1 *Gbps*).	Figure A.1
	Wireless	An infrastructure wireless communication technology (IEEE 802.11g) where Access Points are connected with a wired communication technology having 54Mbps bandwidth.	Figure A.2
	PLC	Three variations of Powerline communication (PLC 1 *Mbps*, PLC 128 *kbps* and PLC 33 *kbps*)	Figure A.3
Failures	Link Failure	Scenario where VMU_2 and VMU_4 are modeled to have failed sending measurements and receiving commands	Figure A.4 and Figure A.5
Sharing	Channel Sharing	Constant traffic of 1 *Mbps* is also going on the same data channel used for sending and receiving measurements and control commands	Figure A.6

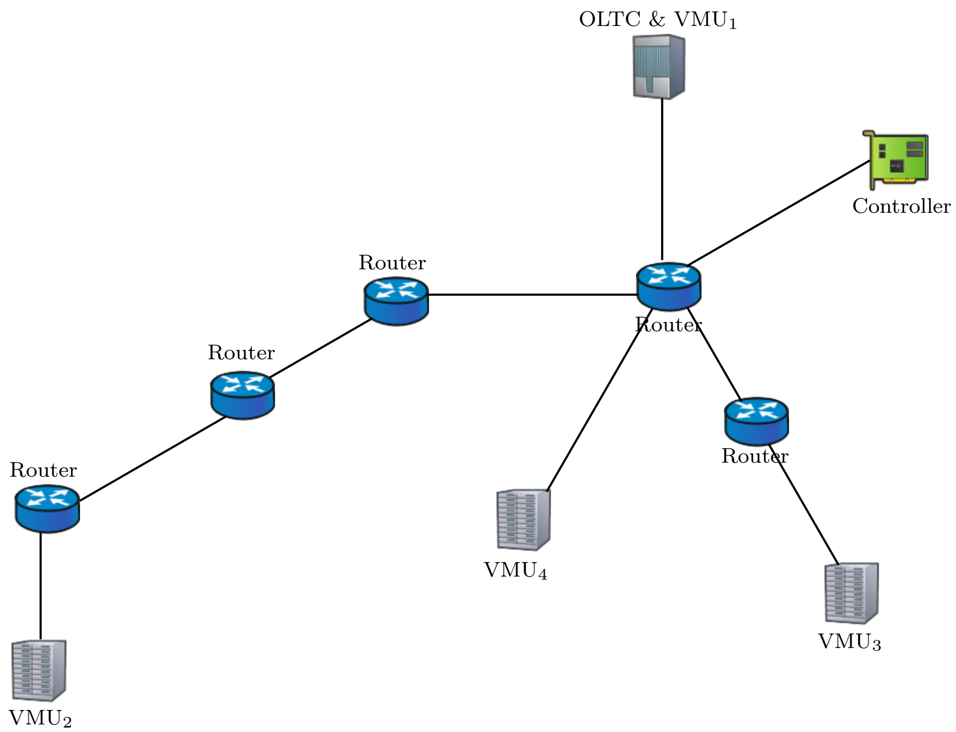


Figure A.1: The communication infrastructure model for Wired communication technologies.

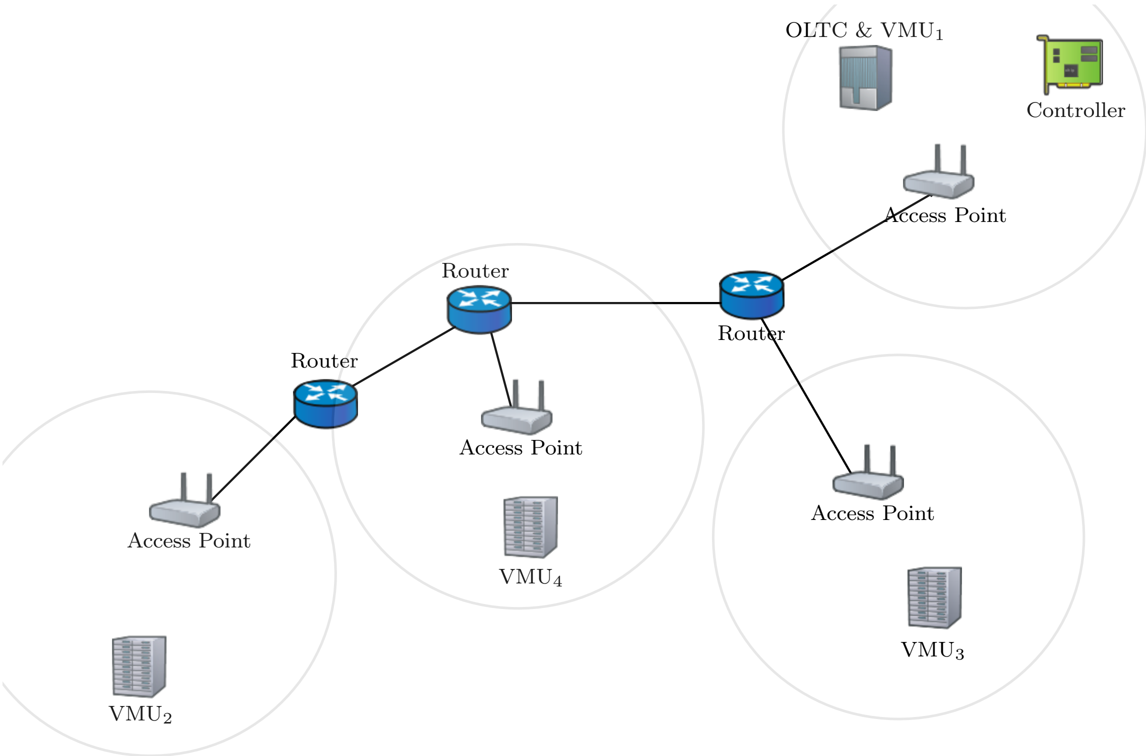


Figure A.2: The communication infrastructure model for infrastructure Wireless technologies.

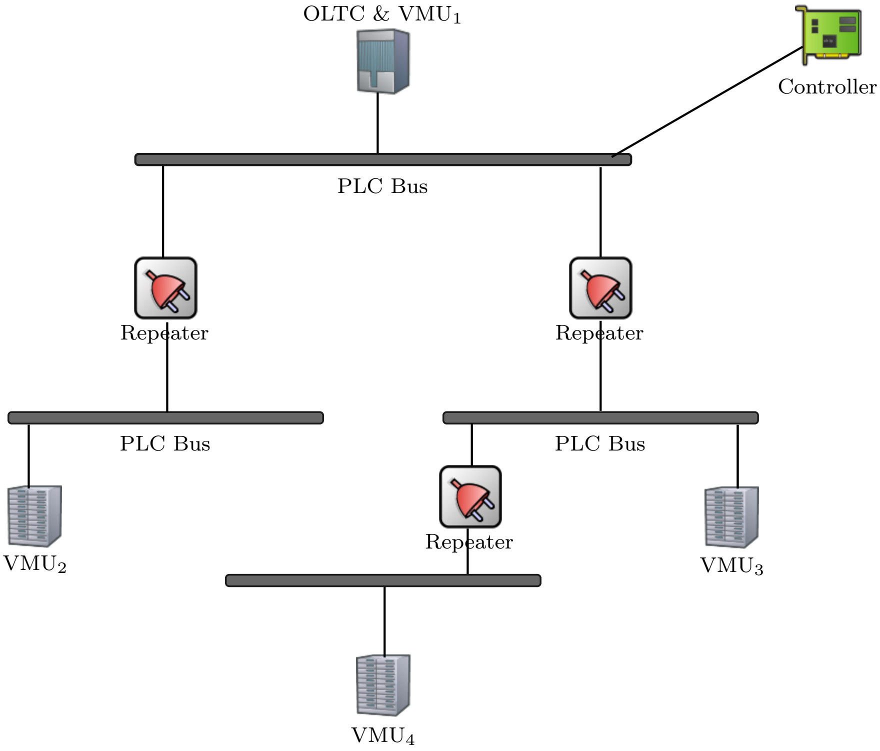


Figure A.3: The communication infrastructure model for Powerline communication technologies.

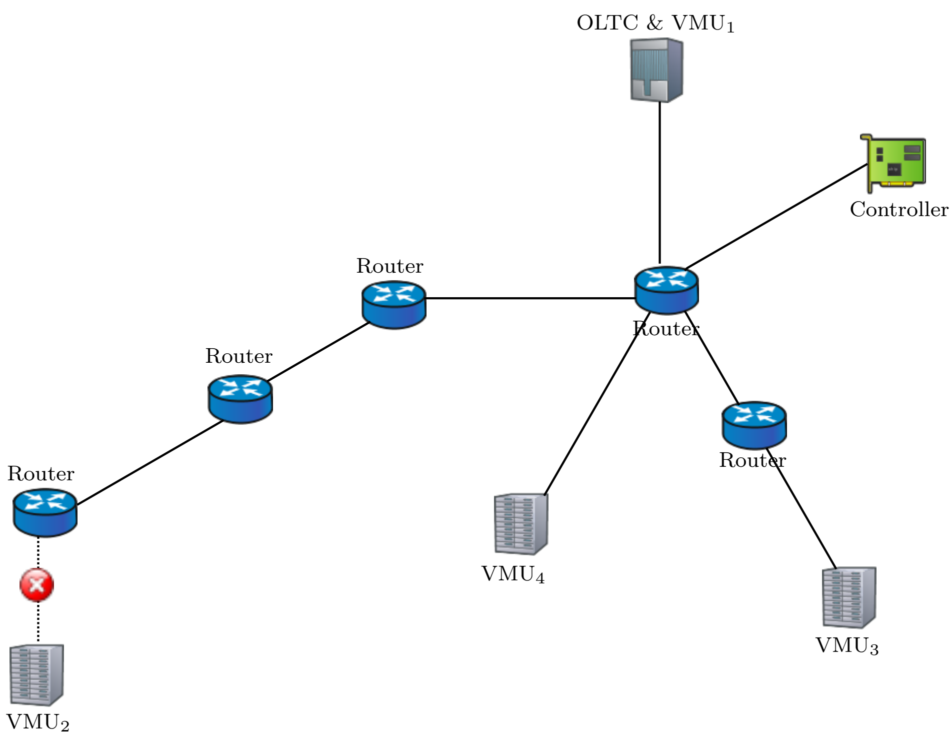


Figure A.4: Scenario, where VMU_2 communication link fails.

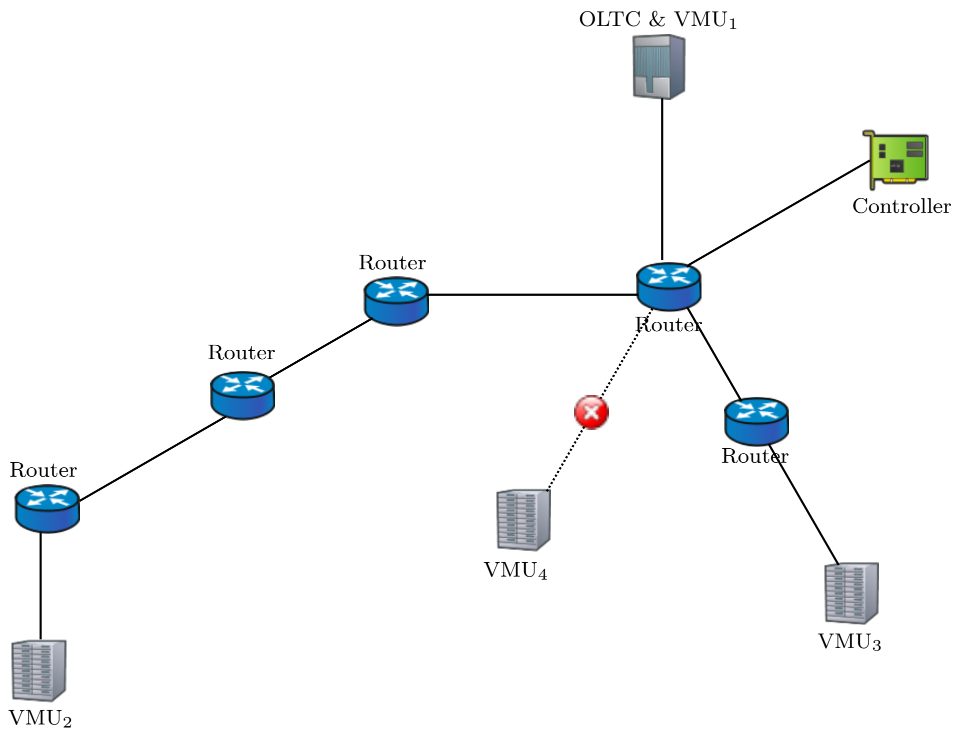


Figure A.5: Scenario, where VMU_4 communication link fails.

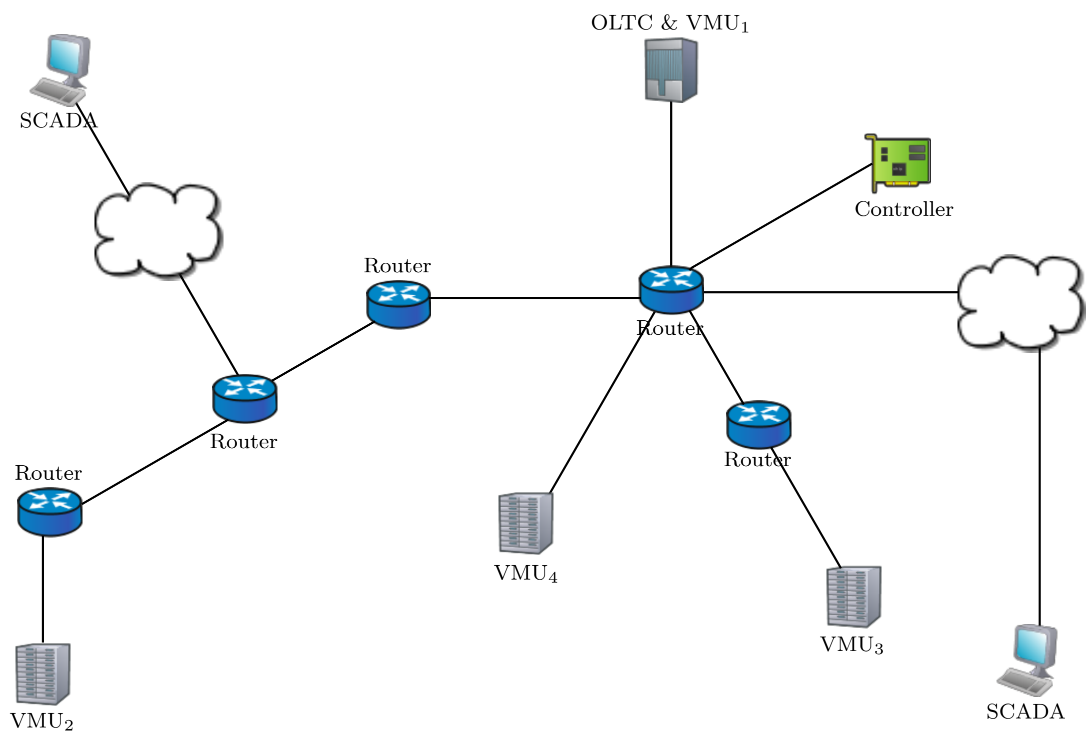


Figure A.6: The communication infrastructure model for sharing of network.

A.2 The Case Study II

Table A.2: A subset of the Case Study III communication infrastructure models and Scenarios.

Category	**Name**	**Description**	**Model**
Technology	Wired	Two variations of wired communication technology with 40 and 1 *Gbps* bandwidths, a star topology and TCP/IP over Ethernet.	Figure A.7
	Wireless	An infrastructure wireless communication technology (IEEE 802.11g) where Access Points are connected with a wired communication technology having 1Gbps bandwidth.	Figure A.8
	PLC	Three variations of Powerline communication with 1 *Mbps*, 128 *kbps* and 33 *kbps* bandwidths (IEEE 1901.1)	Figure A.9
Failures	Link Failure	Communication link between Nearest and farthest PVs experience link Failure. It is therefore, no longer possible to receive measurements or send commands to them.	Figure A.10 and Figure A.11

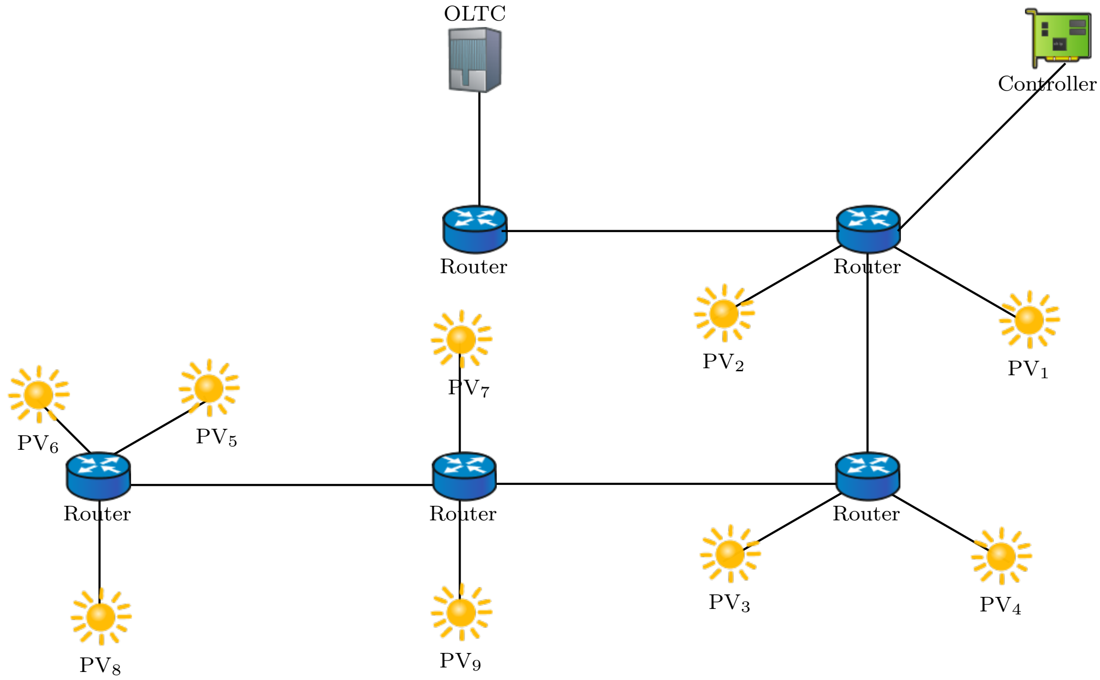


Figure A.7: The communication infrastructure model with Wired communication technology.

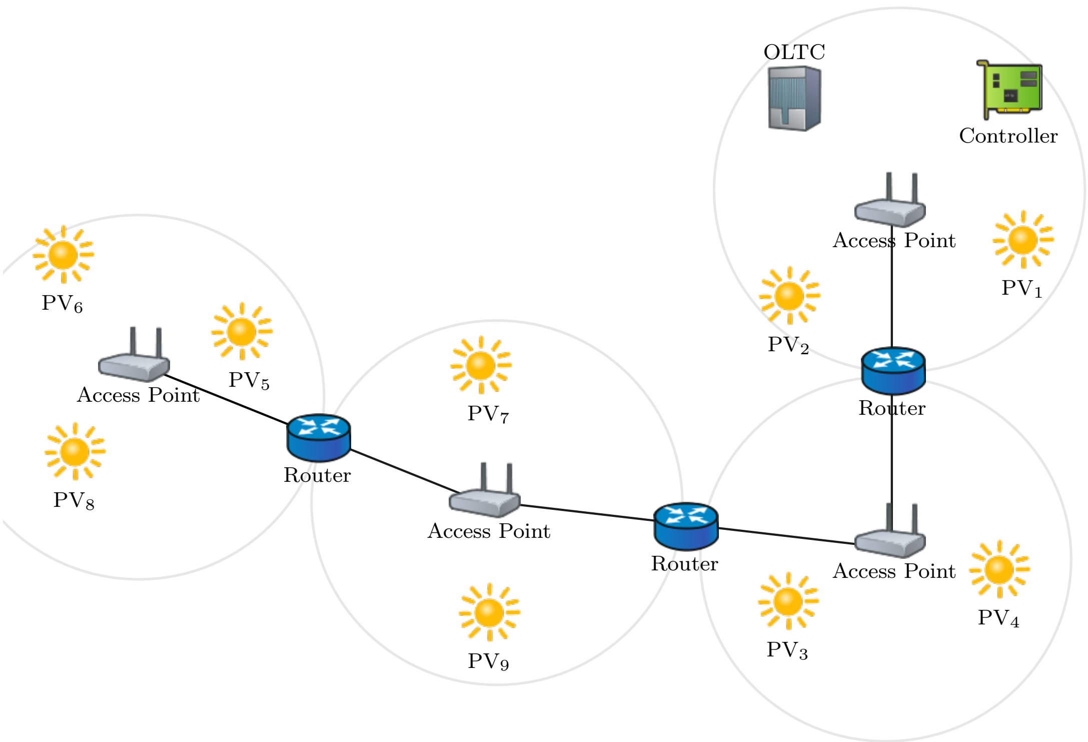


Figure A.8: The communication infrastructure model with Wireless communication technology.

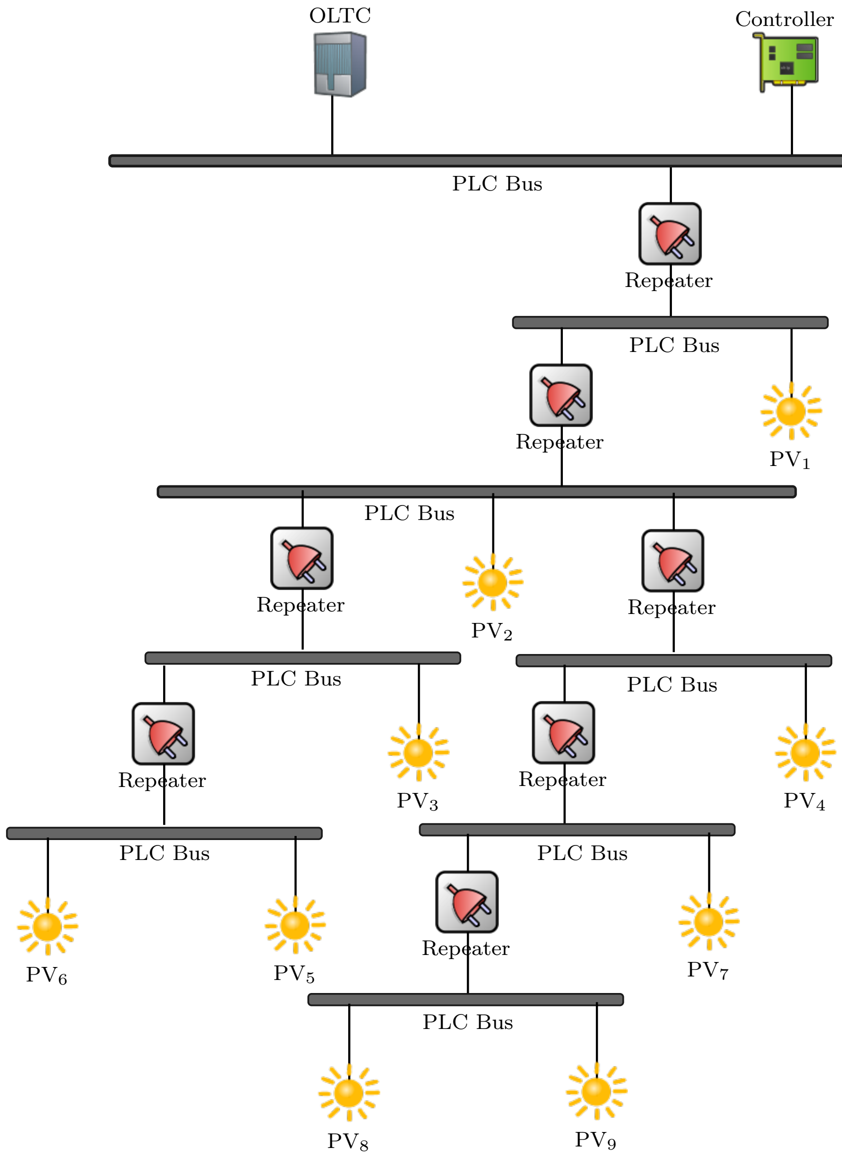


Figure A.9: The communication infrastructure model with Powerline communication technology.

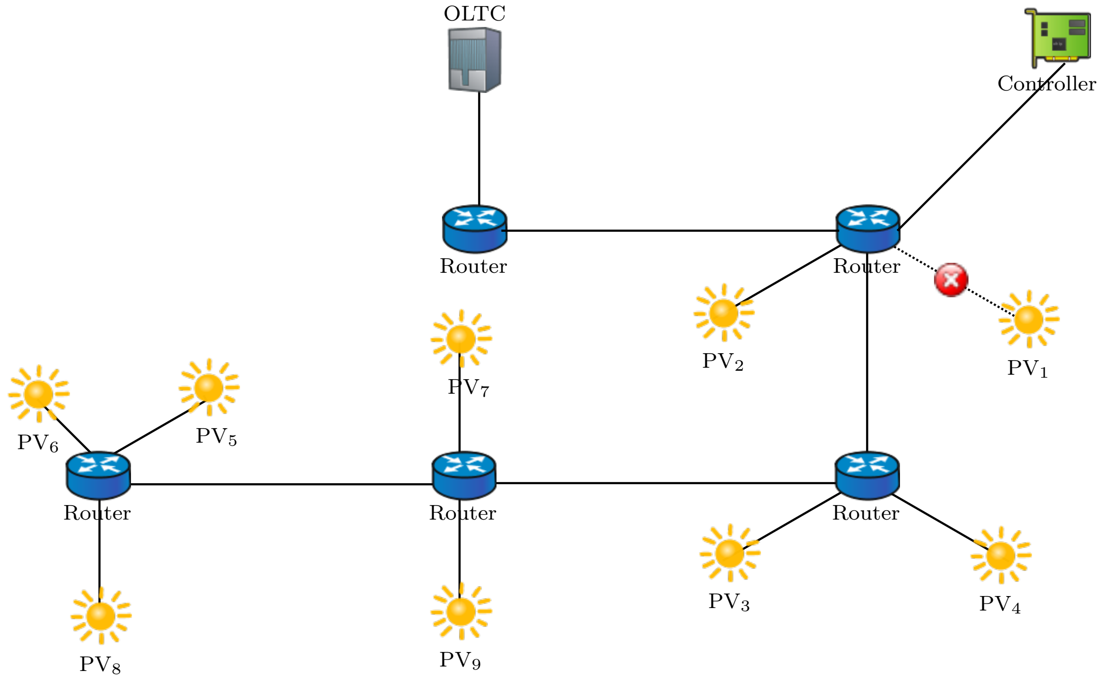


Figure A.10: The communication infrastructure scenario with PV_1 link failure.

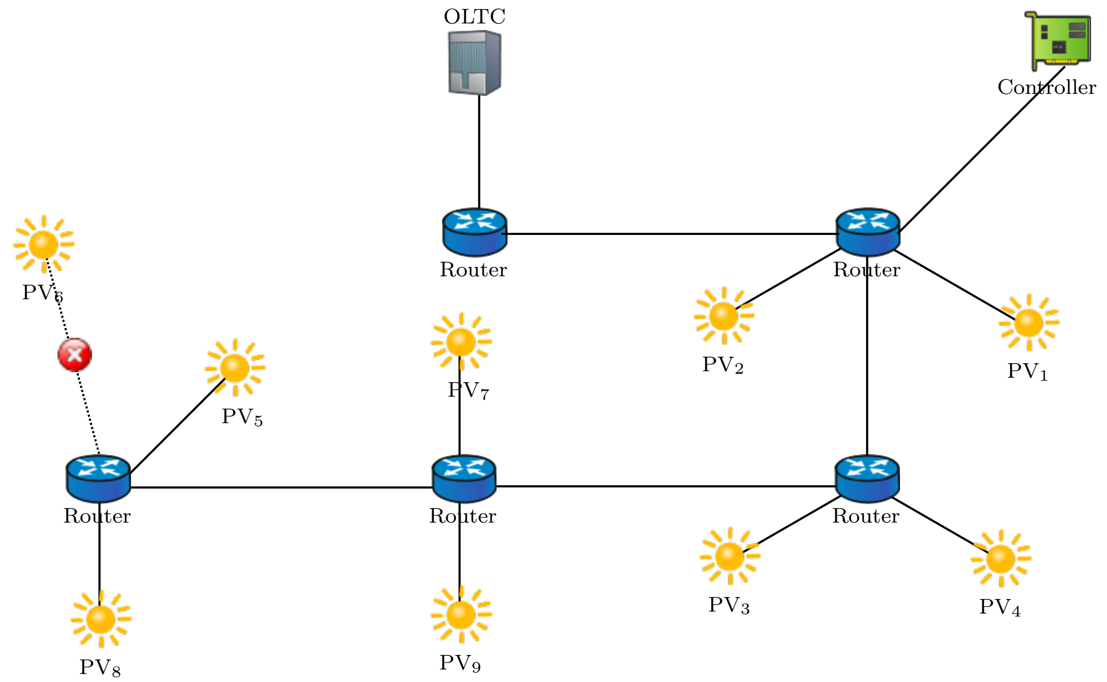


Figure A.11: The communication infrastructure scenario with PV_6 link failure.

A.3 The Case Study III

Table A.3: A subset of the Case Study III communication infrastructure models and Scenarios.

Category	**Name**	**Description**	**Model**
Technology	Wired	Two variation of wired communication technology with 40 and 1 *Gbps* bandwidths, a star topology and TCP/IP over Ethernet.	Figure A.12
	Wireless	An infrastructure wireless communication technology (IEEE 802.11g) where Access Points are connected with a wired communication technology having 1Gbps bandwidth.	Figure A.13
	PLC	Three variations of Powerline communication with 1 *Mbps*, 128 *kbps* and 33 *kbps* bandwidths (IEEE 1901.1)	Figure A.14
Sharing	Channel Sharing	Sharing of channel with other services	Figure A.15

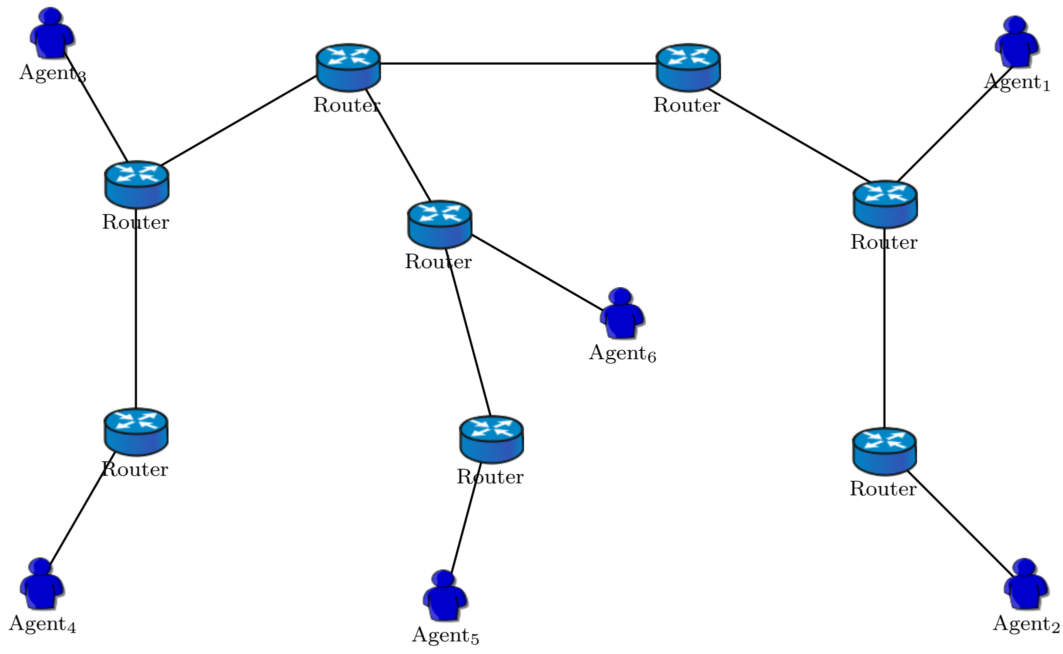


Figure A.12: Wired communication infrastructure model.

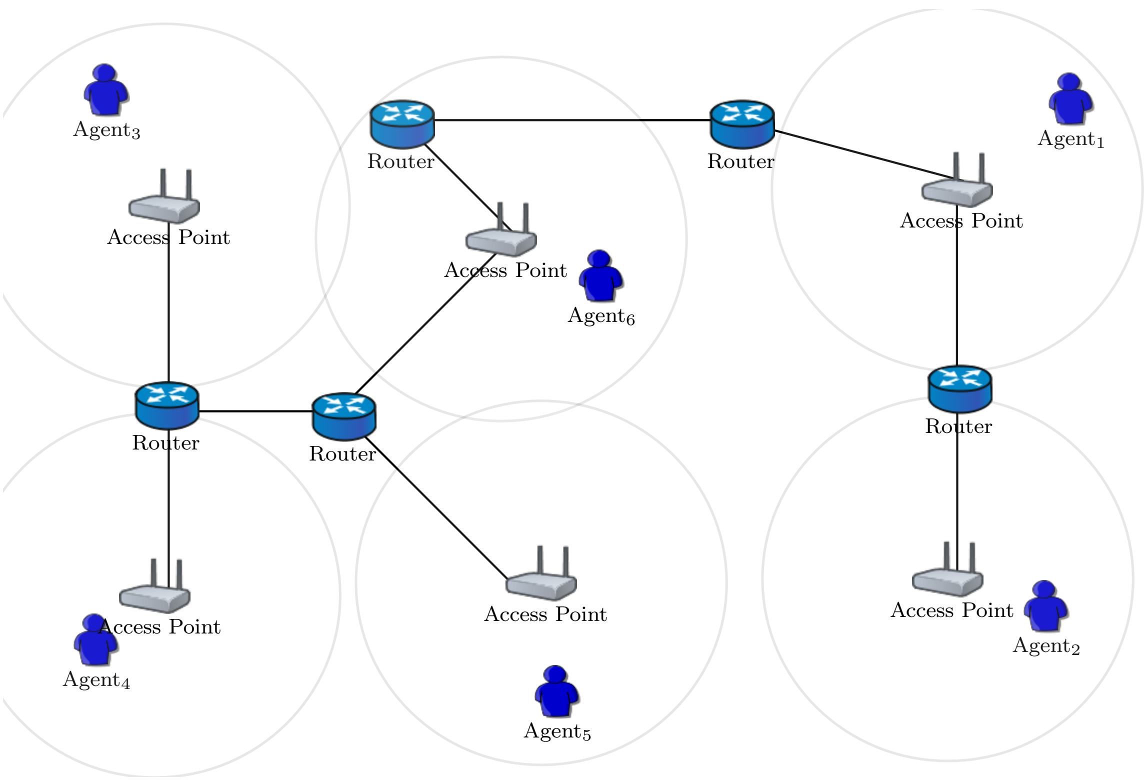


Figure A.13: Wireless communication infrastructure model.

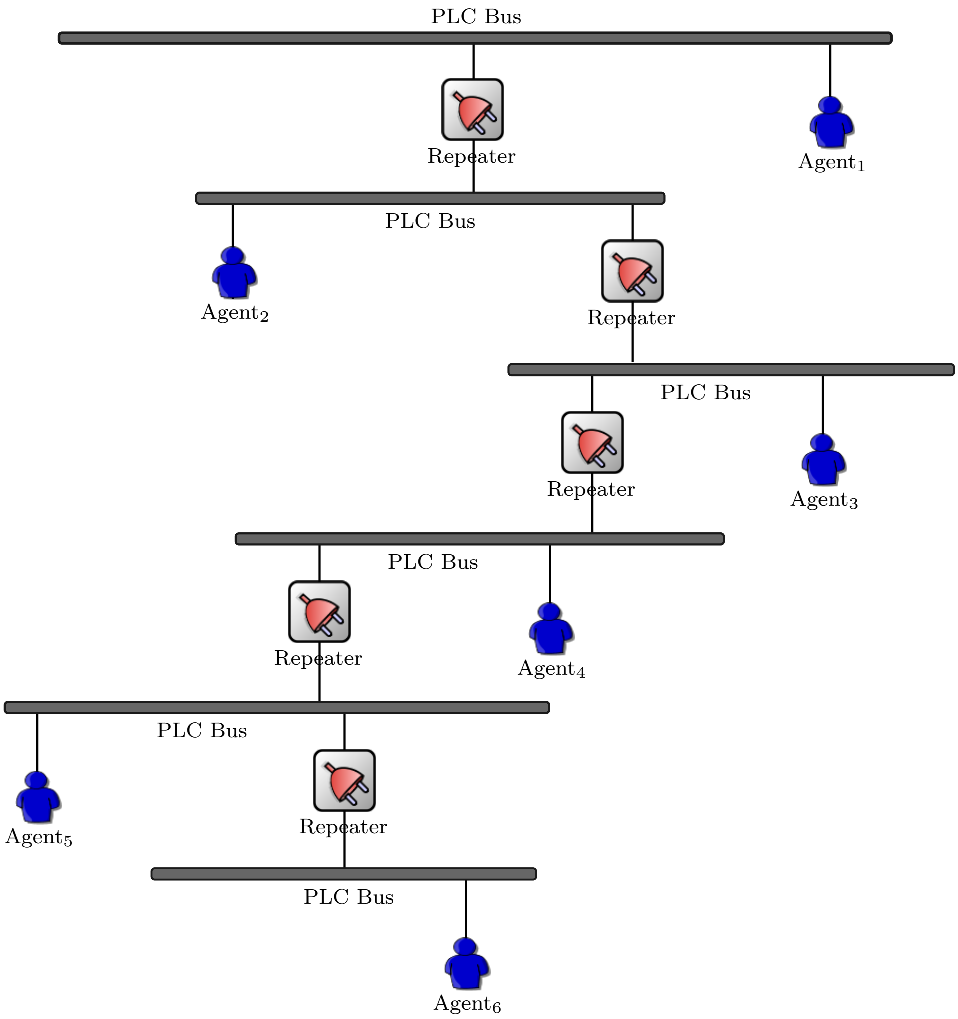


Figure A.14: The communication infrastructure model where the network is being shared with other services.

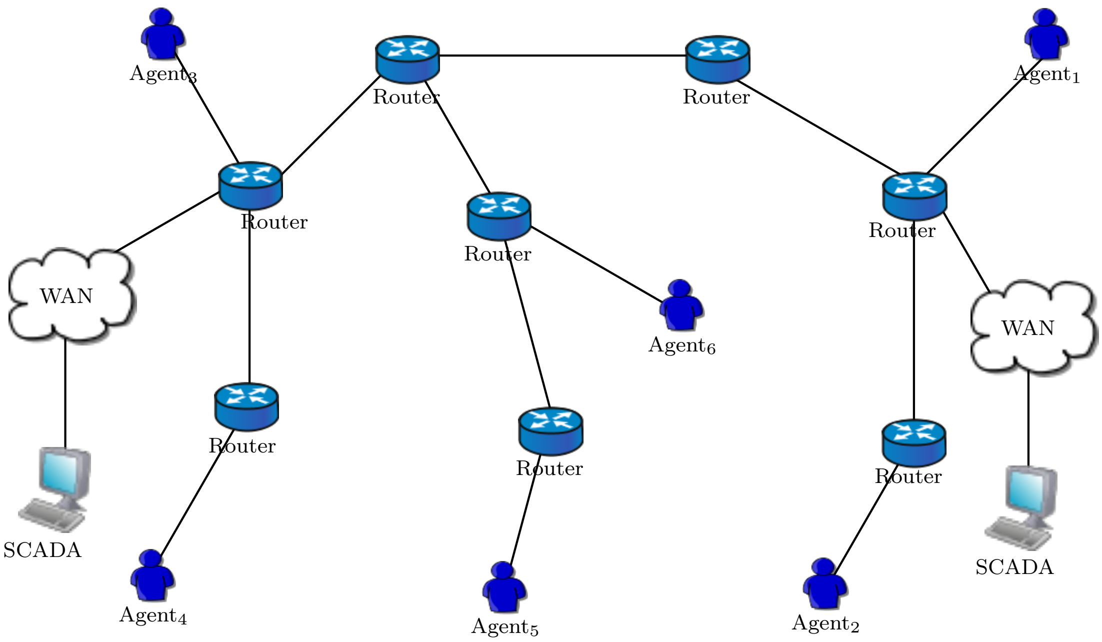


Figure A.15: The communication infrastructure model with Powerline communication technology.

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Curriculum Vitae

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Journal Articles

- Sonia Rauf, Kalim Qureshi, Jawad Haider Kazmi, Muhammad Sarfraz: *An empirical technique to improve MRA imaging.* 06/2015; 83(2)., DOI:10.1016/j.aci.2015.06.002
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Scientific Memberships

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Supervised/Co-supervised Masters Theses

- Sonia Rauf, *A Study of Vessels Extraction Techniques from Magnetic Resonance Angiography (MRA) Images*, 2010, Department of Computer Science, COMSATS Institute of Information Technology, Abbottabad Campus, Pakistan.
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