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Vienna University of Technology

DISSERTATION

Topology Based Safety Relevant and Operational Substation Interlocking Using Graph Theory

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaften

unter der Leitung von
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Kurzfassung

Topologie-basierte Verriegelung von Schaltanlagen bietet einige Vorteile verglichen zu einer Verriegelung mit binären Gleichungen. Mit Hilfe Topologie-basierter Verriegelung ist es möglich mit geringem Aufwand eine sichere Verriegelung für Schaltanlagen zu erreichen und gleichzeitig die Fehlerwahrscheinlichkeit zu reduzieren. Regeln für Topologie-basierte Verriegelung lassen sich unabhängig von der Schaltanlagenkonfiguration formulieren und können dadurch für beliebige Konfigurationen angewendet werden. Die zentrale Idee ist es Topologie-basierte Verriegelung in Feldleitgeräte zu implementieren. Die dezentrale Realisierung in Feldleitgeräten stellt auch gleichzeitige eine redundante Lösung dar. Die Umsetzung in diesen Geräten erfordert eine robuste und vor allem performante Lösung der Topologie-basierten Verriegelung. Die dezentrale Lösung in Feldleitgeräten erfordert aber auch, dass diese Geräte die Schaltstellungen der angeschlossenen Schalter untereinander austauschen. Deshalb werden in dieser Dissertation folgende neue Lösungen für Topologie-basierte Verriegelung vorgestellt:

- Die Verwendung des Standards IEC 61850 stellt eine standardisierte Beschreibung von Schaltanlagen zur Verfügung. Dadurch ist es möglich mit geeigneten Programmen ein Abbild der Schaltanlage grafisch zu erstellen und die Topologie in einer standardisierten Form den Feldleitgeräten zur Verfügung zu stellen. Des weiteren kann mit Hilfe dieses Standards die Kommunikation zwischen den Feldleitgeräten konfiguriert werden und wie in der Arbeit vorgestellt automatisiert erfolgen.

- Für Knoten werden neue Potentiale definiert. Mit Hilfe dieser Potentiale ist es möglich den Typ eines Schalters automatisch zu erkennen und neue betriebsbedingte Verriegelungsbedingungen zu realisieren.

- Für Knoten wird die zusätzliche Eigenschaft “Netzwerkgruppen” eingeführt. Da-

durch ist es möglich Abgänge zusammenzufassen und so Verbindungen zwischen bestimmten Abgängen aus betrieblichen Gründen zu ermöglichen beziehungsweise zu verhindern.

- Für betriebsbedingte Verriegelungsbedingungen wird die Länge paralleler Pfade als Kriterium für die Entscheidung zur Schaltfreigabe oder Schaltverriegelung herangezogen, da sich dieses Kriterium einfach ermitteln lässt. In dieser Arbeit werden daher für verschiedenen Schaltgerätetypen die Längen möglicher paralleler Pfade diskutiert und Regeln für Freigabe und Verriegelung der Schaltgeräte aufgestellt.

- Um die Länge der parallelen Pfade auch für beliebige Konfigurationen verwenden zu können, ist es notwendig diese für ausgewählte Schaltgeräte zu definieren. Deshalb wird die Länge als neue Eigenschaft für Schaltgeräte in dieser Arbeit eingeführt und für die Schaltgeräte entsprechend definiert.

- Modifikationen für die in der Arbeit verwendeten Suchstrategien Breitensuche und Tiefensuche werden vorgestellt. Änderungen sind für die Breitensuche notwendig, um bei unterschiedlich definierten Längen von Schaltelementen trotzdem noch den kürzesten parallelen Pfad identifizieren zu können. Die Tiefensuche muss angepasst werde, um überhaupt in einer Schaltanlagenkonfiguration alle relevanten parallelen Pfade finden zu können.

- Zusätzlich wird analysiert inwieweit sich die Topologie einer Anlage reduzieren lässt, wenn die Verriegelung dezentral in Feldleitgeräten gelöst wird. Für die reduzierte Toplogie werden deshalb nur jene Schaltgeräte ausgewählt, die für die Verriegelungsentscheidungen in benachbarten Feldleitgeräten benötigt werden. Die Reduktion der Topologie verringert den Suchaufwand und die Auslastung der Kommunikationsleitung, da nur jene Schaltgerätestellung ausgetauscht werden müssen die auch für Verriegelungsentscheidungen notwendig sind.

- Für die Identifizierung des Schaltanlagentyps werden in der Dissertation Kriterien zur automatischen Detektion eingeführt. Diese Kriterien werden auch verwendet, um die Gültigkeit der Schaltanlagenkonfiguration zu testen. Zusätzlich werden weitere Algorithmen vorgestellt um die Topologie zu testen und um sicherzustellen, dass die modifizierten Suchverfahren zu gültigen Lösungen kommen.

Abstract

Topology based interlocking provides reasonable advantages for switchgear interlocking. Compared to Boolean equations used for interlocking, topology based interlocking is able to reduce engineering demand and to reduce the source of errors. If the rules for topology based interlocking are defined and verified, they can be applied to any configuration. The idea is to implement topology based interlocking in bay controllers because that provides decentralised and redundant interlocking decisions. But interlocking in bay controllers requires robust and performance solutions and needs communication to keep the topology in all bay controllers current. Therefore following new solutions for realisation are presented in this thesis:

- The standard IEC 61850 is used to provide a standardised description of substations. Suitable editors can be used to draw the single line digram of a substation and store the standardised description of the substation. This standard can also be used to configure the communication for bay controllers to exchange switch positions. This fact is used for realisation to set up the communication to exchange switch positions automatically.
- New node potentials are introduced for automatic detection of switches and to allow a large variety of operational interlocking conditions.
- Network groups are used as an additional criterion for nodes. This allows to group feeders and prevent connections between feeders that must not be connected.
- For operational interlocking the length of parallel paths is used as criterion to generate enable or interlock signals. This criterion is easy to evaluate but requires some extensions. The length of paths are discussed and differentiated for possible switch types.

- Therefore switches are assigned with a new property - the length. The length of switches is normally set to one. For special types of switches a description is given of how the length has to be set depending on the configuration.
- The length of switches and in general the substation configuration requires a modification for the search strategies breadth-first search and depth-first search. The modifications guarantee that the shortest parallel paths and all relevant parallel paths for operational interlocking will be found.
- Additional analyses is done on the reduction of the topology. Switches that are not taken into account in other bays for interlocking are identified. Eliminating these switches from the topology increases the performance. Therefore the reduced topology decreases the search time and the load on the communication bus of substations to make the system more efficient.
- Criteria are defined to automatically detect the substation type.
- These criteria can be used to check the validity of the configuration as well. Additional algorithms and needed adaptation are presented to check the reachability and validity of the configuration to guarantee that the proposed search algorithms are working.

1 Motivation

"There's a way to do it better - find it."
Thomas Alva Edison (1847 - 1931)

Life today depends very much on electric energy supply. A secure and reliable supply is important for the economy and even social stability. Rising demand on electric energy and higher share of renewable sources lead to higher and fluctuating power flow. Higher fluctuations stress the grid. To avoid dangerous situations for the grid switching actions to control the power flow have to be done. Switching in electrical stations has to be done carefully because different types of switches are used for different purposes. To prevent hazardous switch actions interlocking for the switches is used.

The way interlocking is actually done in switchgears, is with Boolean equations. The Boolean equations take switch positions of surrounding switches into account and derive an interlock or enable signal for a switch. For example, switch one is allowed to be opened when switch two and three are closed and switch four or five is open. In large switchgears these Boolean equations have a high demand at the first installation and also when the substation is extended. Setting up these equations is prone to errors and hazardous switch actions may result.

A way to reduce failures in switchgears is to stop using Boolean equations for interlocking and use topology based interlocking. Research in topology based interlocking was already done several years ago. Some problems were solved but for some solutions Boolean equations were still needed. Preparing the topology and defining switch types for the algorithms had to be done by hand as well.

I found a new way to use topology based interlocking without the need of additional

Boolean equations. The idea is to simply draw the switchgear in a suitable editor that supports the standard IEC 61850 for switchgear description. Further on the standardised switchgear description is used to identify the topology, the switch types, check the validity of the switchgear configuration and to provide topology based interlocking automatically. The necessary communication to exchange switch positions in the switchgear will be configured automatically to provide safe and reliable interlocking in any switchgear. Topology based interlocking is improved and new solutions for topology based operational interlocking conditions are introduced.

2 Introduction

This chapter gives an introduction to the three topics needed for topology based interlocking of switchgears. Section 2.1 provides information on switchgears. Switch types are presented as well as typical switchgear configurations. Section 2.2 presents the need of interlocking. Safety relevant and operational interlocking conditions are presented. Substation interlocking with Boolean equations is state of the art and presented with an example. Section 2.3 gives the definition of graphs, discusses different data structure, and presents two basic search strategies. Furthermore a graphic interpretation of a switchgear is given with an introduction to topology based interlocking.

2.1 Switchgear

Electrical switchgears are link elements in electrical grids. Switchgears control the electrical power flow, distribute energy and connect power plants or loads to the grid. Switchgears have one or more voltage levels. For each voltage level, they have at least one connection point, called busbar. Busbars are needed to connect feeders (adjacent lines, cables, transformers) and couplings, when there is more than one busbar. The necessary switches to connect and safely disconnect the feeders are grouped in bays. The switches are designed for different purposes and therefore interlocking (see section 2.2) is needed to ensure a save operation in a switchgear. Interlocking depends on the type of switch, the switch position and the type of the substation. Therefore these devices and configurations are introduced in this section.

Figure 2.1 shows an example of a substation with two voltage levels and the necessary switching devices. Bold lines represent busbars, points indicate that the crossing lines

are electrically connected, voltage levels are surrounded by doted lines and one feeder and a coupling are framed with a dash dotted line. All figures in this thesis showing any switchgear configuration are represented by a single line diagram[1]. To provide necessary information of the state in the grid (e.g. for protective devices), additional equipment like current and voltage transformers have to be installed as well. These devices are not directly needed for interlocking decisions[2], they are not shown in the given single line diagrams in this thesis.

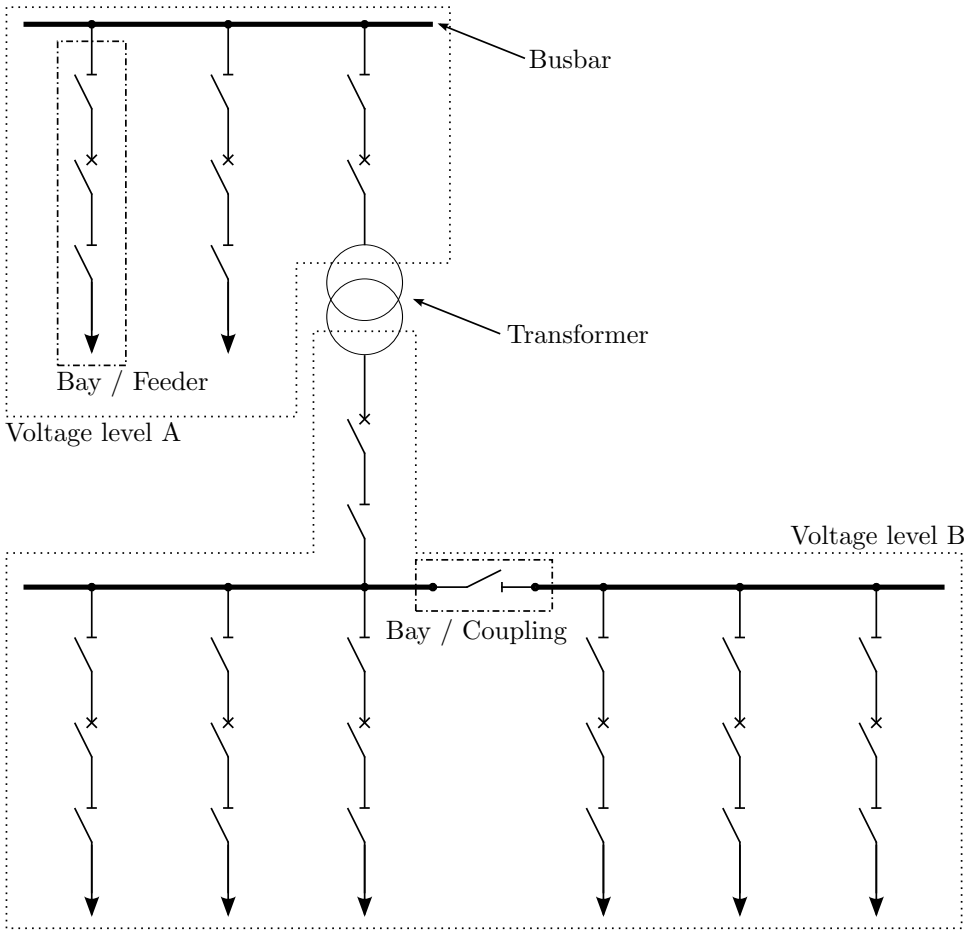


Figure 2.1: Example of a substation to illustrate busbars, voltage levels and bays

[1] A single line diagram is "A simplified notation for representing a threephase power system in which the polyphase links are represented by their equivalent single line." [1, p. 533]
[2] Voltage transformers might be needed to avoid coupling asynchronous parts of the grid

2.1.1 Types of Switching Devices

This section gives an overview of the most common types of switches that are used in switchgears and a brief description of the capability of the switches.

Disconnectors are switching devices with the ability to ensure an isolating distance, if they are in the "open position". The isolating voltage is one characteristic value for a disconnector. Another characteristic value is the current under "normal" and "abnormal" condition. This type of switch is not capable to switch under load. Only low currents because of capacitive charging of equipment up to 0.5 A [2, p. 427] are possible. A definition for the isolation distance is given in [2, p. 427]: "Isolating distances are gaps of specified dielectric strength in gases or liquids in the open current paths of switching devices. They must comply with special conditions for the protection of personal and installations and their existence must be clearly perceptible when the switching device is open." Figure 2.2(a) shows the symbol used for disconnectors in single line diagrams.

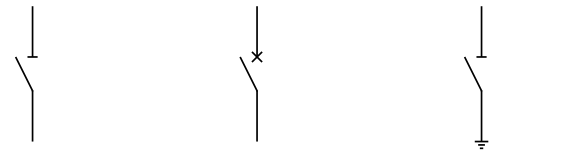
Circuit breakers are, in difference to disconnectors, elements which are designed to switch current under normal and even under fault conditions, but are not able to provide an isolating distance. Values like the short circuit current $I_K^{"}$, the current in normal operation I_N and the voltage are used to select a circuit breaker. The short circuit current for a switch can be calculated with the standard DIN EN 60909 [3]. Figure 2.2(b) shows the symbol used for circuit breakers in single line diagrams.

Earthing switches are special types of disconnectors that connect isolated areas to ground in order to provide secure working conditions for maintenance in a switchgear. Figure 2.2(c) shows the symbol used for earthing switches in single line diagrams.

Figure 2.2 shows the symbols of the previous described switch elements similar to the definition in the standard IEC 60617-7 [4]. The labeling of devices in figures is done in accordance with the standard IEC 81346-2 [5] with the following designations (where x is a number):

- QAx for circuit breakers
- QBx for disconnectors
- QCx for earting switches

Furthermore the standard IEC 81346-2 defines the entire description of a system or object so labels for other elements like bays, transformers and busbars are defined.



(a) disconnector (b) circuit breaker (c) earthing switch

Figure 2.2: Examples for different switches

- For bays, depending on the operating voltage, letters from "A" to "N" are used in combination with the the number of the bay. The label for example "E1" indicates the first bay of a substation with a voltage lower than 220 kV and greater or equal than 110 kV.
- Busbars above operated with a higher voltage than 1 kV are labeled with "WA" and the number of the busbar. For busbars with lower voltages "WC" is used in combination with the number of the busbar.
- Transformers are labeled with "TA" and the number of the transformer.

The labels are combined to describe the structure of the substation. For example "E1-QA1" describes the first circuit breaker in the first bay of the substation.

2.1.2 Switch Position

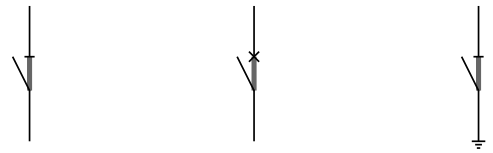
For interlocking decisions and to indicate it in a control room, it is necessary to identify the position of each switch. Auxiliary contacts are installed in each switch in order to deliver the information about the switch state. Two auxiliary contacts give redundancy and indicate the following states:

- open
- closed
- intermediate position
- failure in auxiliary supply

Open and **closed** are the two steady operation states of a switch. One auxiliary contact has the state "on", the other one "off". The state **intermediate** indicates that the switch is moving or (due to a fault) stuck in an intermediate position which is neither closed

and nor open. This state is indicated if both contacts have the state "on". A **failure in auxiliary supply** is indicated if both contacts are "off".

Standard [5] specifies how to draw the switch devices but does not define how to draw open and closed switches in a single line diagram. To demonstrate the effect of switch positions for interlocking decisions it is necessary to show the positions in single line diagram. Therefore the drawing as in figure 2.2 will be used to indicate open switches. Closed switches will be drawn as shown in figure 2.3 with a thick gray line connecting the switch contacts.



(a) disconnector (b) circuit breaker (c) earthing switch

Figure 2.3: Closed switches

2.1.3 Types of Switchgears

Switchgears can have different configurations depending on the demand for reliability and flexibility in the grid and for the adjacent feeders. The most common switchgear types are listed here with a brief description.

A simple configuration is a **single busbar**. This configuration is suitable for smaller stations. A single line diagram is shown in figure 2.4. There is no redundancy in the

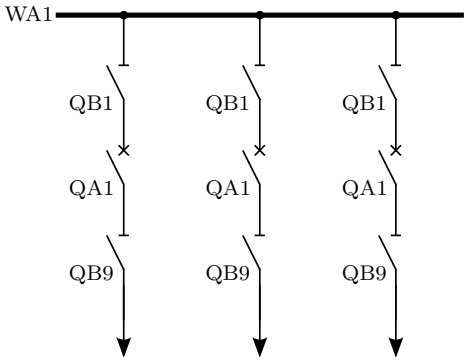


Figure 2.4: Single busbar

switchgear. A failure or maintenance work on the busbar causes an interruption on all connected lines or feeders. Only if all lines or loads can be supplied from another station the continuous power supply is guaranteed. If redundancy is needed in a substation, other configurations can be used to guarantee continuous power supply:

- double busbar
- triple busbar
- ring busbar
- 1 ½-breaker
- two circuit breaker

A **double busbar** configuration has, compared to a single busbar configuration, an additional busbar and an adjacent disconnector to connect the feeder to one of the two busbars. Furthermore, in order to change the connection of one feeder from one to another busbar or to couple its busbars in operation, an extra bay with a coupling is needed. A single line diagram of a sample configuration is given in figure 2.5.

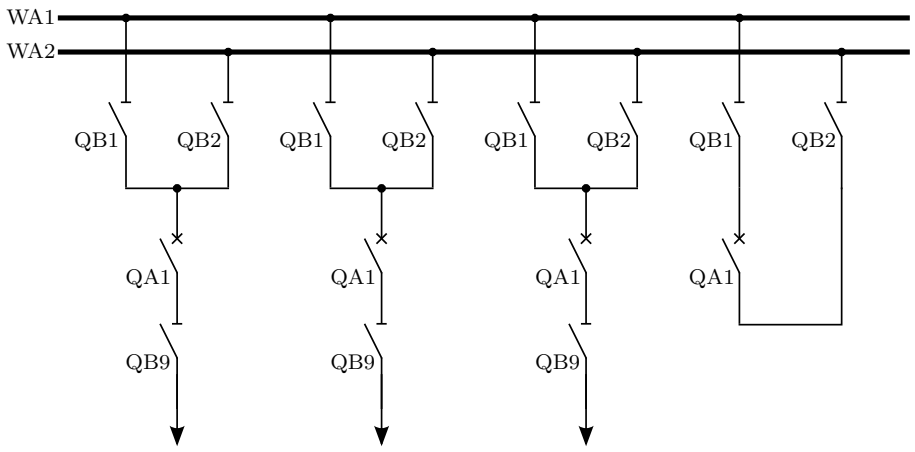


Figure 2.5: Double busbar

A **triple busbar** (or multiple busbar) has, compared to the double busbar, one more busbar and because of the configuration, a more complex coupling to ensure all combinations of busbar couplings. Figure 2.6 shows an example single line diagram of a triple busbar configuration.

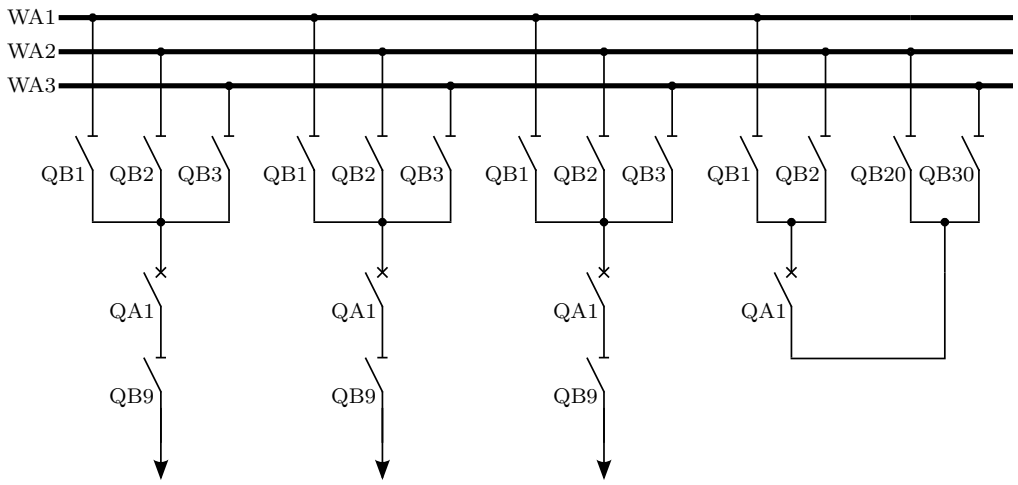


Figure 2.6: Triple busbar

Splitting busbars into two or more sections provides additional possibilities to connect loads to different sources, or to separate feeders because of operational reasons. To couple sectionalized busbars, a longitudinal disconnector can be used. This has the disadvantage that this element can only be switched without load. But a coupling with a circuit breaker is able to open or close the coupling under load. For double or multiple busbars, there are often longitudinal disconnectors in parallel to a coupling or additional switches in series to enable multiple coupling configurations. It is possible to connect the busbars under load with the coupling and afterwards close the longitudinal disconnector. This reduces the amount of circuit breakers in a substation and enables a high flexibility to couple more busbars under load and keep them coupled.

Instead of a double busbar (figure 2.5) the feeders can be connected to the busbars with a disconnector circuit breaker and disconnector combination for each busbar. In this case, the configuration is called a **2-breaker** method due to the breakers for each busbar. The advantage is that every circuit breaker of a feeder can be removed for maintenance without an interruption. A single line diagram is shown in figure 2.7.

For single, double or multiple busbars an **auxiliary busbar** is another option to maintain a circuit breaker without interruption of a feeder. The advantage compared to the 2-breaker method is that the second circuit breaker is not needed, but an extra busbar and additional disconnectors. The disadvantage is that only one circuit breaker can be bypassed with an auxiliary busbar. A single line diagram of a double busbar with

an auxiliary busbar (marked with “WA7”) is shown in figure 2.8.

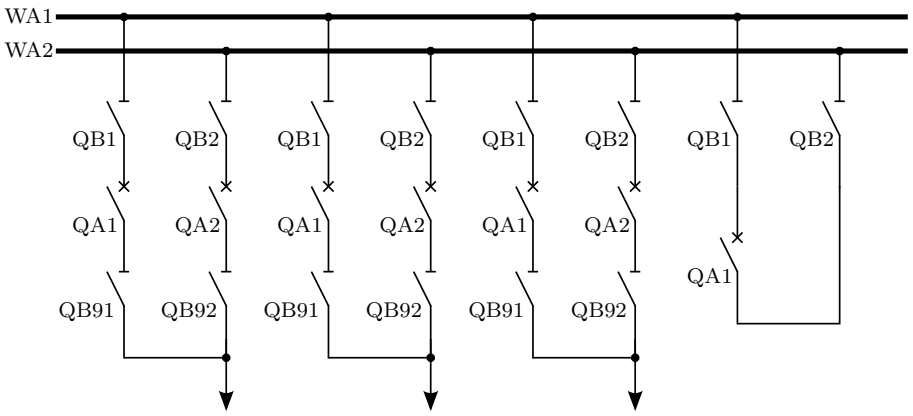


Figure 2.7: 2-breaker method

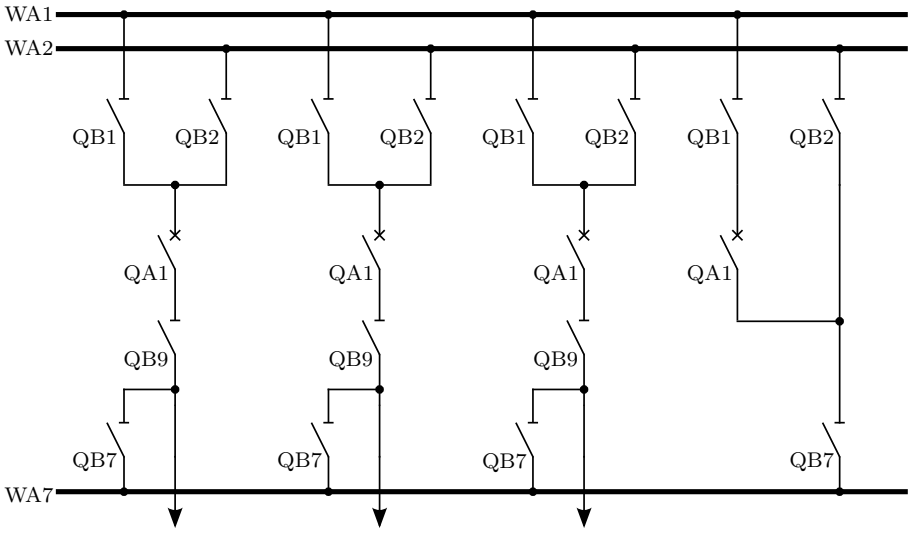


Figure 2.8: Double busbar with auxiliary busbar

Another configuration in order to maintain circuit breakers without interruption in power supply is the **1 ½-breaker method**. As shown in figure 2.9, there are three circuit breakers for two feeders, which results in 1 ½-breaker for each feeder. Compared to the 2-breaker method, for two feeders one circuit breaker can be saved.

With a ring busbar configuration disconnection of a circuit breaker without interrupt-

ing any feeder can be realised. The configuration requires only one breaker per feeder compared to the 1 ½-breaker method. It has not an equal flexibility for a higher number of feeders, in order to control the power flow.

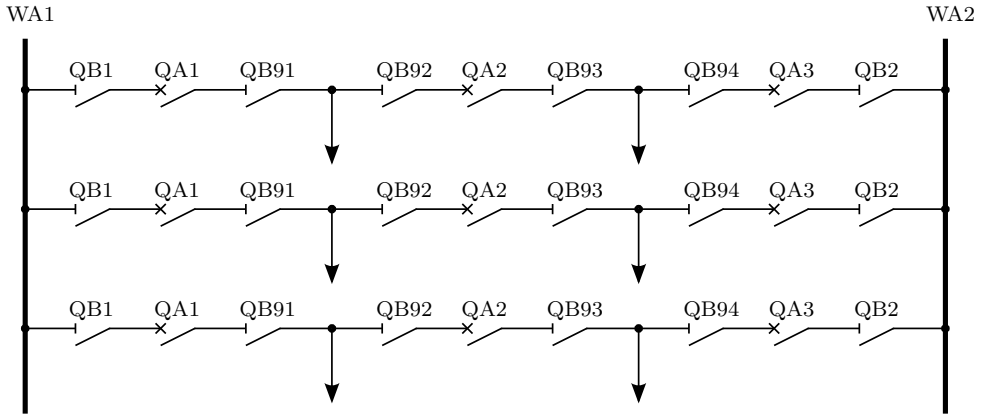


Figure 2.9: 1 ½-breaker method

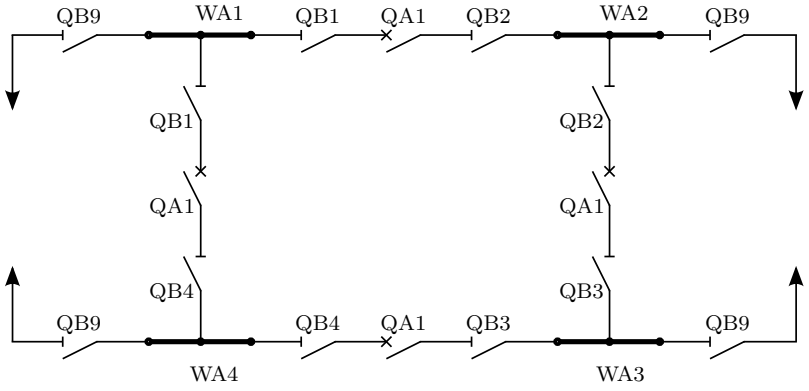
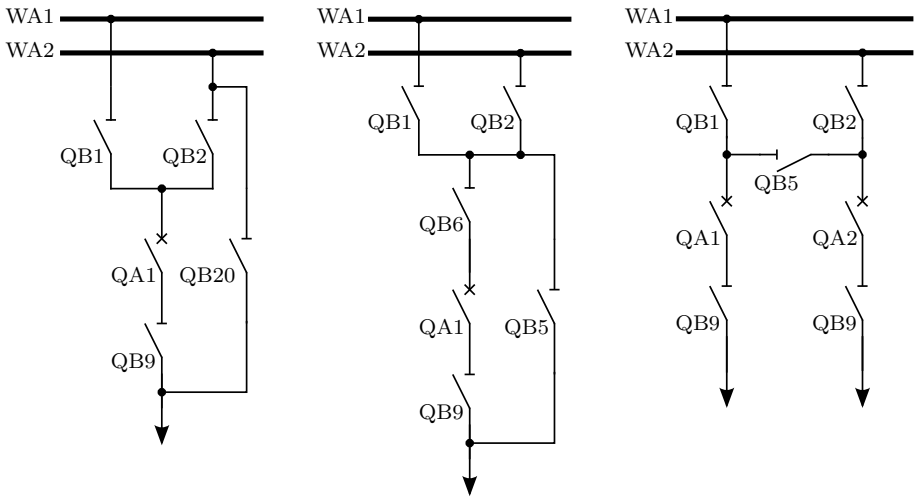


Figure 2.10: Ring busbar

For single, double and multiple busbar systems, some extra equipment can be added to increase the availability of power supply during maintenance. A **bypass switch** (see. 2.11(a) switch Q_{B20}) or a **shunt disconnector** (see 2.11(b) switch Q_{B5}) for example can be used to bypass a circuit breaker for maintenance. For the same reason, one or more **auxiliary busbars** are installed in larger substations. A **cross-tie switch** (see 2.11(c) switch Q_{B5}) can be used to directly connect two feeders, and to isolate these feeders from the busbars (if needed). Another option is to include a **transfer busbar**

to increase flexibility, or to include a composite double busbar / bypass bus.



(a) bypass switch (b) shunt disconnector (c) cross-tie switch

Figure 2.11: Special switch configurations

2.1.4 Communication in Switchgears

Switchgears have a high demand of communication. Switching commands, switch positions for correct interlocking decisions, as well as data from measuring devices needs to be transmitted to the protective devices or to substation controls. In history, analogue data communication was used, which had a high demand on wiring. As remote controls, computers and automation in substations came up, digital data transmission was introduced in substations. Every vendor developed and used proprietary protocols for digital data exchange. Interoperability was not given between different vendors. To provide interoperability and other advantages, the standard IEC 61850 [6] was introduced in 2004. This standard provides:

- one protocol for the entire communication in a substation (including process bus, field bus and substation control),
- interoperability between devices from different vendors,

- future proof by providing communication mechanisms for functions without defining a specific communication technology and
- a specific format (Substation Configuration Language (SCL)) to store the entire configuration of a substation.

Another benefit is the increased safety. “Not only signals like measured current value is transmitted, but as well the scaling factor and the according physical dimension to guarantee the correct interpretation of the transmitted or received value” [7, p. 5]. Part six defines the standardized description of a substation with the SCL. This description is based on the eXtensibel Markup Language (XML) and has three main sections:

- substation configuration,
- device configuration and
- communication configuration.

”SCL specifies a hierarchy of configuration files that enable multiple levels of the system to be described in unambiguous and standardized XML files. The various SCL files include System Specification Description (SSD), IED Capability Description (ICD), Substation Configuration Description (SCD), and Configured IED Description (CID) files. All these files are constructed in the same methods and format but have different scopes depending on the need.” [8, p. 6]

2.2 Interlocking

Interlocking in switchgears is used to differentiate between allowed and not allowed switching actions. The signals are defined in the standard DIN IEC 60050-351 [9, p. 282f.]

- interlocking signal that blocks operation of the switch and
- enabling signal that permits the operation of the switch.

Interlocking or enabling signals are based on positions of adjacent switches. Safety relevant interlocking guarantees that no element in the substation is destroyed. Operational interlocking is used for operational reasons e.g. to keep the switching sequence.

2.2.1 Safety Relevant Interlocking

The rules for safety relevant interlocking are given in the thesis [10, p. 20] and in the thesis [11, p. 8]. They can also be derived from the standards DIN VDE 0101 and DIN VDE 0670. The rules are valid for any configuration of the substation. The correct usage of the rules assures that no element in the substation is destroyed.

- A disconnector must not be operated under load.
- Live parts of a switchgear must not be connected to earth.
- Switches for isolating must guarantee the isolation distance.
- Asynchronous voltages must not be coupled.
- Switches in intermediate position must not be stressed.

2.2.2 Operational Interlocking

Contrary to the safety relevant interlocking the operational interlocking depends on the substation configuration. Not obeying operational interlocking will not necessarily cause a malfunction in the substation. Operational interlocking can be used to activate or deactivate an auxiliary busbar, to check for continuous power supply, keep the correct switching sequence or other defined functions. These rules are defined by the switchgear operator and can therefore be very diverse. In [10, p. 21] and in [11, p. 176ff.] examples for operational interlocking are presented. The most common ones are:

- keep switching sequence
- do not forward earth potential
- usage of transfer or auxiliary busbar is allowed
- keep capacitive currents small
- allow coupling of busbars
- guarantee continuous power supply
- prevent to couple feeders that must not be coupled (keep limits of short circuit power, network groups)
- not energize a transformer with a disconnector

2.2.3 Boolean Equations

Enabling signals are formulated in form of Boolean equations. If the enabling signal is "false", the switch is interlocked and the operation of this switch is locked. In the figure 2.12 a simple substation configuration is given.

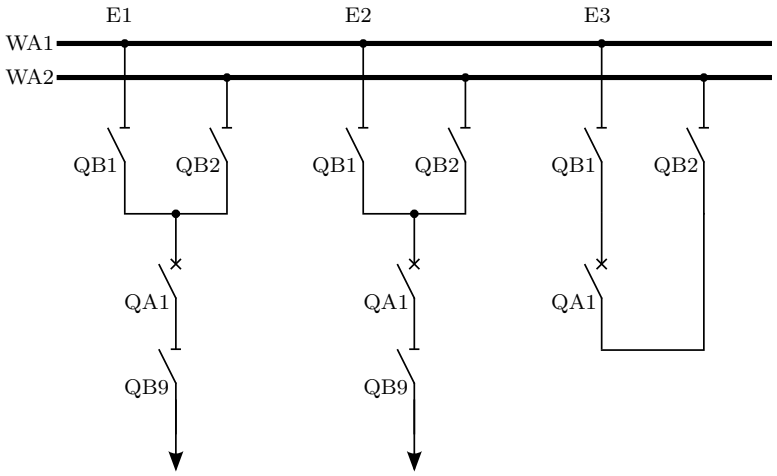
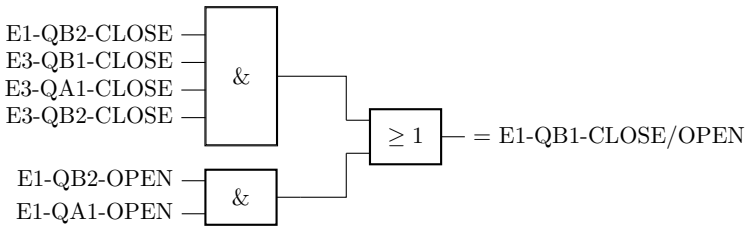


Figure 2.12: Exemplary substations with double busbar

The presented Boolean equations give an indication of the complex problem. In the figure, the switch QB1 of the bay E1 needs the positions of five other switches for secure operation. The equation 2.1 derives enable signals for this switch and does not differentiate between closing or opening. On the one hand operation of switch E1-QB1 is allowed if a parallel path exists. Therefore switch E2-QB2 needs to be closed and the busbars WA1 and WA2 have to be coupled with the closed switches E3-QB1, E3-QA1 and E3-QB2. This is checked with the upper left part[3] of the equation 2.1. On the other hand opening of the switch is allowed if the disconnector E1-QB1 is allowed if the switch does not make or break currents. Therefore it is necessary that switch E1-QB2 and E1-QA1 are open. This is checked with the lower left part[4] of the equation 2.1 . If one of the two conditions is true the operation of the switch E1-QB1 is allowed - checked with the right part[5] of equation 2.1. For safety relevant interlocking conditions no information of the bay E2 is needed. Therefore the switches do not appear in the

[3] & block with four inputs
[4] & block with 2 inputs
[5] ≥ 1 block

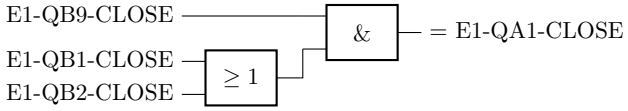
equation. If in larger substations coupling of feeders is restricted due to operational reasons, then the disconnectors of other bays have to be taken into account too.



(2.1)

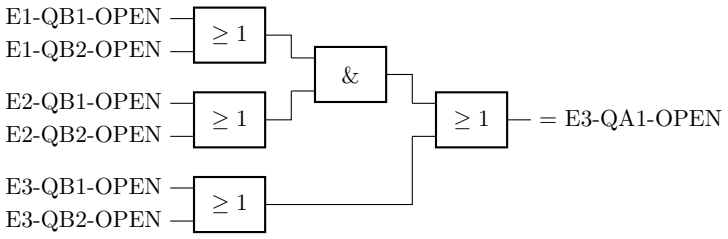
To derive interlocking decisions for switch E1-QB9 only the state of switch E1-QA1 is needed. If E1-QA1 is open then E1-QB1 is allowed to be opened or closed.

An operational interlocking equation to keep the switching sequence - close disconnector before closing the circuit breaker - is presented in equation 2.2. Because continuous power supply for the feeders is wanted no enable signal is defined. Opening the switch could interrupt the loads, if the feeder is not connected to another substation.



(2.2)

For opening the coupling circuit breaker E3-QA1, the switch states of all adjacent switches of the busbars are needed as listed in equation 2.3. One has to guarantee, that the coupling is not opened as long as any feeder is connected to more than one busbar with disconnectors. Restrictions for closing the circuit breaker E3-QA1 are similar to the switch E1-QA1, when keeping the switching sequence is wanted. Additionally if some feeders must not be coupled in a substation, the switching positions of all other feeders are needed to prevent impermissible coupling. For larger substations, these equations get a lot more complex because of larger numbers of feeders, busbars and additional operational interlocking.



(2.3)

2.3 Graph Theory

2.3.1 Introduction to Graphs

Graph theory provides powerful tools to describe and handle a lot of different problems, for example when relations or connections have to be analysed. An example is navigation. A graph consists of edges and nodes - for navigation streets can be interpreted as edges and crossings as nodes. The graph theory provides search algorithms to find routes along the edges in order to navigate from one point to another within a graph. With additional criteria (e.g. length for each edge) the shortest path between two points is evaluated. Other examples are electrical circuits, communication networks, transportation systems and social networks. The next paragraph gives a mathematical definition[6] of a graph and an example and diagrams of the graph:
"A *graph* G is an ordered triple $(V(G), E(G), \psi_G)$ consisting of a nonempty set $V(G)$ of *vertices*, a set $E(G)$, disjoint from $V(G)$, of *edges*, and an *incidence function* ψ_G that associates with each edge of G an unordered pair of (not necessarily distinct) vertices of G. If e is an edge and u and v are vertices such that $\psi_G(e) = u, v$, then e is said to *join* u and v; the vertices u and v are called the ends of e" [12, p. 1]. The following example of a graph G [12, p. 1] shows how the nodes and edges are defined. Figure 2.13 shows two different diagrams of the same graph G:

$$G = (V(G), E(G), \psi_G)$$

where

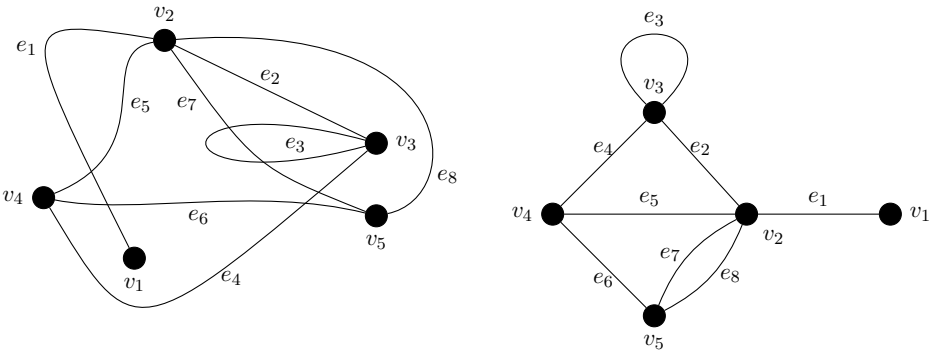
$$V(G) = \{v_1, v_2, v_3, v_4, v_5\}$$
$$E(G) = \{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8\}$$

and ψ_G is defined by

$$\psi_G(e_1) = v_1, v_2, \psi_G(e_2) = v_2, v_3, \psi_G(e_3) = v_3, v_3, \psi_G(e_4) = v_3, v_4,$$
$$\psi_G(e_5) = v_2, v_4, \psi_G(e_6) = v_4, v_5, \psi_G(e_7) = v_2, v_5, \psi_G(e_8) = v_2, v_5$$

Special edges in graph G are edges e_3, e_7 and e_8. Edge e_3 is called a loop because the edge starts and ends at the same nodes. e_7 and e_8 are parallel edges because both edges have the same start node and the same end node.

[6] The here cited literature uses the term vertices instead of nodes, but further on in the thesis the term node will be used.



(a) Diagram of graph G (b) Another diagram of graph G

Figure 2.13: Examples for graph G [12, p. 2]

To work on graphs, different data structures can be used. Each structure has advantages and disadvantages. A trade off between memory space and computation time has to be made. Three commonly used structures are introduced: For a graph G with n nodes and m edges:

- the $(n \times n)$ matrix A is the **adjacency matrix** where $A[i, j]$ represents the number of edges that are joining the nodes v_i and v_j. [12, p. 7] The adjacency matrix of the graph in figure 2.13 is shown in equation 2.4:

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 2 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 2 & 0 & 1 & 0 \end{pmatrix} \tag{2.4}$$

- the $(n \times m)$ matrix M is the **incidence matrix** of G where $M[i, j]$ is the number of instances that v_i and e_j are incident [12, p. 7]. The incidence matrix of the graph in figure 2.13 is shown in equation 2.5:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 2 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{pmatrix} \tag{2.5}$$

- the **adjacency list** "efficiently represents sparse graphs by using linked lists to store neighbours adjacent to each node." [13, p. 151] The adjacency list of the graph in figure 2.13 is shown in figure 2.14:

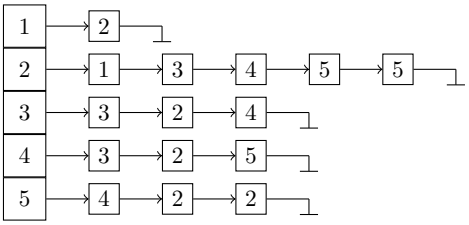


Figure 2.14: Adjacency list for the graph in figure 2.13

An adjacency matrix needs a lot of memory to store a graph, even for sparse graphs. However, the advantage is that the adjacency matrix provides a fast test if a direct connection exists between two nodes. Furthermore new edges can be added or deleted easily in this structure. An incidence matrix needs in general more memory to store graphs compared to the adjacency matrix. But for sparse graphs when $n > m$ the incidence matrix needs less memory to store the graph than the adjacency matrix. The adjacency list needs even less memory and has advantages for traversing a graph. A detailed comparison between the different structures is given in [13, p. 152] and [14, p. 23].

An example will present the difference in needed memory and calculation time. Therefore a sectionalized double busbar substation with ten feeders and a coupling is chosen (see figure 2.15). The number of nodes is:

- 4 busbar nodes (N5)
- 2 nodes in the coupling (N2)
- 3 nodes for each feeder (N1, N2 and N3)

This results in 36 nodes. An adjacency matrix needs to store that structure $36 \cdot 36 = 1296$ elements. For this substation with 36 nodes and 47 switches, An incidence matrix would need elements 1692. An adjacency list needs 36 lists, one for each node. The exemplary nodes are marked in figure 2.15. N1, N2 and N3 are needed in each feeder so they appear ten times for the substation. N4 is needed for each busbar section, therefore this node appears four times. N5 appears twice in the coupling. Table 2.1 shows the needed elements that have to be stored for each node type. Summing up all elements for the 36

lists shows that 94 elements have to be stored, which is less than eight percent of the adjacency matrix. Larger substations increase the difference in memory and calculation time needed between the adjacency matrix and the adjacency list. The adjacency list grows linear while the matrix increases quadratic. For computers calculation time and storage is not a big issue, but in bay controllers calculation time and memory is limited so that the adjacency list provides reasonable advantages.

For searching adjacent nodes similar effects can be shown:

- With the adjacency matrix 36 elements need to be analysed to find all adjacent nodes to one node.

- Using the adjacency list for a node of N4 type, seven elements have to be analysed. For a node of type N1, only one element has to be analysed. An average of $94/36 = 2.6\dot{1}$ nodes per list reduces the average calculation time to find all adjacent nodes to approximately less than eight percent.

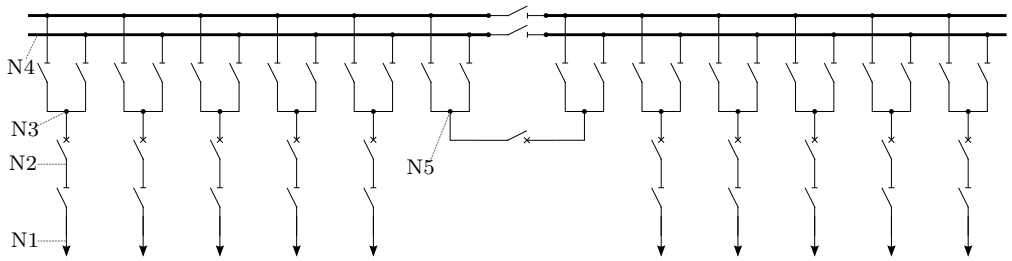


Figure 2.15: Substations with double busbar and ten feeders and exemplary marked nodes N1...N5

Table 2.1: Number of nodes for different node types of the example given in figure 2.15

Node Type	Needed Elements	Number of Lists
N1	1	10
N2	2	10
N3	3	10
N4	7	4
N5	3	2

2.3.2 Petri Nets

Petri nets are bipartite graphs. [15] Petri nets are suitable to describe transitions and concurrent computation. Operation of a switch can be seen as an transition from one to another state. But they have one major disadvantage that is not suitable for topology based interlocking. Petri nets can describe transitions that change a state. The problem is that Petri nets need an initial state as starting point. That means for example after a failure in the system all switches need to be opened to reach an initial state. This is a problem because, to reach that state, unsafe "not interlocked switch operation" is needed to open all switches. Furthermore, live feeders have to be disconnected and therefore an interruption in power supply occurs. Another point is that all possible states and transitions need to be described, which does not give any benefit compared to boolean equations. This are the reasons why Petri nets are not used for topology based interlocking in this thesis.

2.3.3 Search Algorithms for Graphs

Searching algorithms for graphs are needed to search for connected nodes or to traverse the entire graph. The breadth-first search (BFS) and depth-first search (DFS) are two mechanisms to visit each node and each edge in a graph. Both algorithms are very simple and basic algorithms. So they can be used for any graph. This includes planar[7] and non planar graphs. This is important because single line diagrams of substation configurations are in general not planar. Ring busbar, 1 ½-breaker method, 2-breaker method and double busbar configurations can be represented by planar graphs. Multiple busbar configurations with more than two busbars can only be represented by non planar graphs.

BFS and DFS can be used to search the entire graph. In most cases it does not make a difference which algorithm is used, in others it does make a difference. BFS can be used to find the shortest path between two nodes [13, p. 162] and DFS is preferred for finding parallel path [13, p. 173]. The difference between the algorithms is the way the nodes are discovered. [13, p.169]

- BFS stores the discovered nodes in a queue (first-in, first-out). This means exploring the graph is done from the oldest node in the queue and radiates out slowly from the starting point. [13, p. 169]

[7] A planar graph can be drawn without crossing edges.

- DFS stores the nodes in a stack (last-in, first-out). From the newest node the next node is searched, to explore the graph. If new nodes are found, the algorithm searches in the stack for nodes with undiscovered nodes to continue searching for new nodes. This method quickly leads away from the starting point. [13, p. 169]

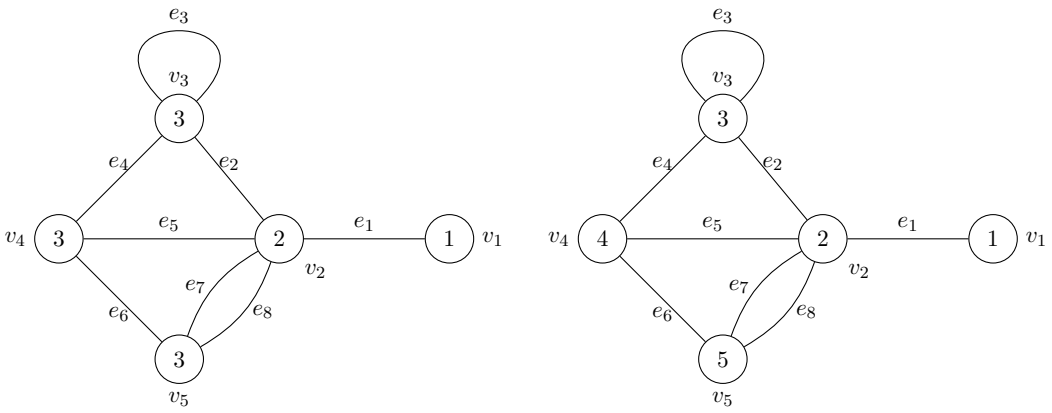
A description of the BFS algorithm can be found in [13, p. 162] or in [16, p. 124]. For DFS a description can be found in [13, p. 171f] or in [16, p. 98]. Figure 8.1 and 8.2 in the appendix shows a flow chart of the BFS and DFS algorithm. To illustrate the differences of the search algorithms, an example is shown in figure 2.13. The graph presented in figure 2.13(b) is used to demonstrate how BFS and DFS are working. Figure 2.16(a) presents the results for BFS and figure 2.16(b) presents the results for DFS. Node v_1 is chosen as starting node for both search algorithms. The numbers inside the nodes indicate the sequence of finding the nodes with each search algorithm.
BFS:

- Starting at the v_1 node, BFS discovers the e_1 edge leading to the v_2 node.
- In the next step the adjacent edges of the v_2 node are discovers as following:
  - The e_2 edge leads to the v_3 node.
  - The e_5 edge leads to the v_4 node.
  - The e_7 edge leads to the v_5 node.
  - The e_8 edge which does not lead to an undiscovered node.
- In the next step the adjacent edges of the v_3 node are discovered:
  - The e_3 edge which is a loop, leads to already discovered v_3 node.
  - The e_4 edge leads to another already discovered node.
- The last step discovers the e_6 edge which does not lead to a new node. So the entire graph is traversed with BFS.

DFS:

- Starting at the v_1 node DFS discovers the e_1 edge leading to the v_2 node.
- In the next step the e_2 edge leading to the v_3 node.
- Then the e_3 edge is evaluated which does not lead to a new node.

- The e_4 edge leads then to the v_4 node.
- Analysing the e_5 edge leads to the already discovered v_2 node.
- Further on the e_6 edge leads to the v_5 node.
- The e_7 edge leads to the already discovered v_2 node.
- Finally the last undiscovered e_8 edge does not lead to an undiscovered node. So DFS traversed the entire graph.



(a) BFS sequence of discovered nodes

(b) DFS sequence of discovered nodes

Figure 2.16: Example of BFS and DFS discovering nodes for graph G of figure 2.13(b)

2.3.4 Graphic Interpretation of a Switchgear

A graph is a valuable tool to describe a substation. The graphic interpretation is proposed in this section for the example substation shown in figure 2.12. The connection points (busbars or connection points between two or more switches) in a substation are the nodes of a graph. The switching elements (disconnectors, circuit breakers) are the edges that connect the nodes of a substation. Figure 2.17 shows a representative graph for the substation which has been introduced in figure 2.12. This graph shows all nodes and edges independent of the switch position. Switch positions are used as additional criteria for the edges of the graph. The search strategies check for each switch the position. If the switch is in the closed position the search strategy uses this edge to search for the adjacent node. If the switch is in the opened position the search strategy ignores

the edge in the graph and does not search for the adjacent node of this edge.

Figures 2.19 2.20 2.21, 2.22 and 2.23 show the graph of the substation updated with the switch positions in the way the graph is interpreted by the search strategy.

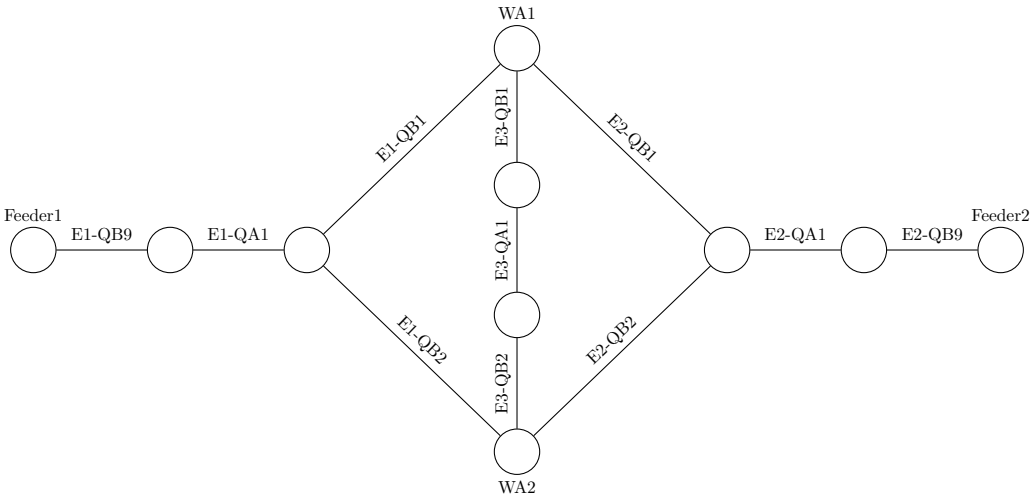


Figure 2.17: Graph of the switchgear shown in figure 2.12

Figure 2.18 shows the substation of figure 2.12 with closed and open switches. Feeder E1 is connected to busbar WA1 and feeder E2 is connected to busbar WA2. The coupling E3 connects both busbars and feeders. The effects on the graph are shown in figure 2.19.

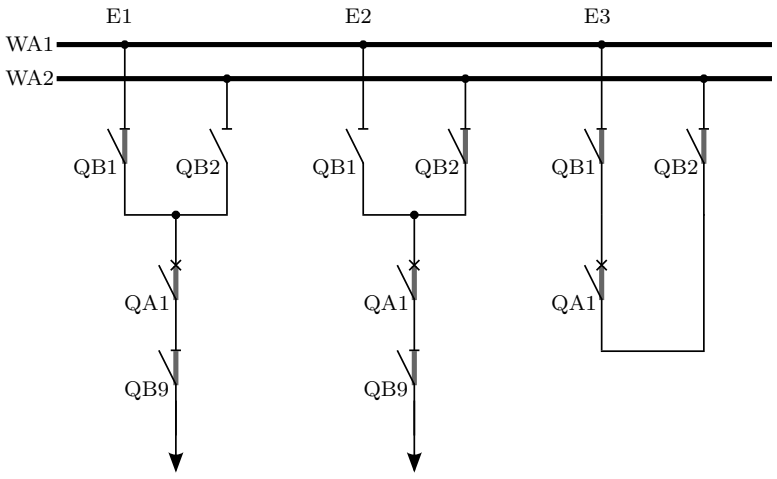


Figure 2.18: Exemplary double busbar substations with opened and closed switches

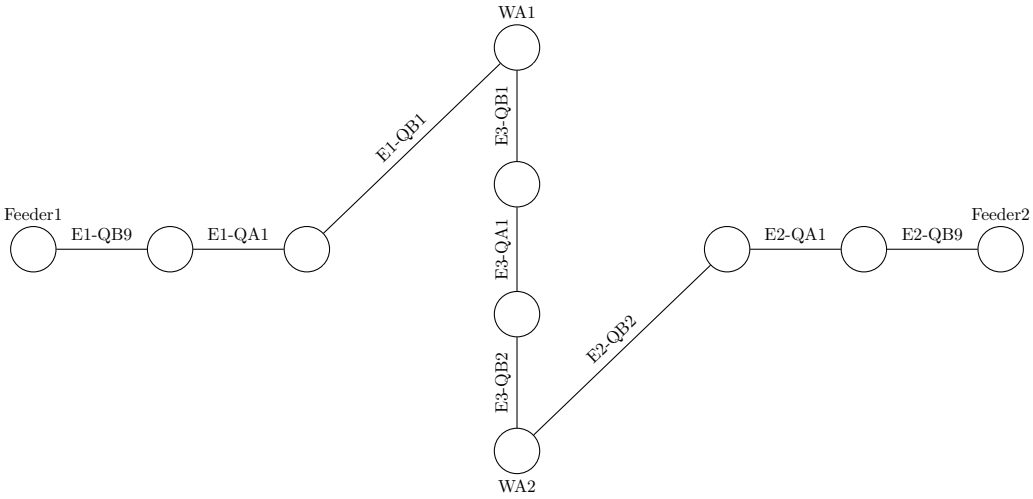


Figure 2.19: Graph of the switchgear in figure 2.12 updated with switch positions as presented in figure 2.18

2.3.5 Topology Based Interlocking of a Switchgear

After setting up the graph of a switchgear, topology based interlocking can be applied. Further steps are described in [11] and [10] and explained for the substation in figure 2.12. To generate enable or interlock signals for switches, additional information is needed which is not available in the topology represented by the graph in figure 2.19. To get the information which kind of nodes the switch connects, potentials for the nodes are introduced. This is done by using the following values:

- **E** ... **E**arth nodes for earthing
- **S** ... **S**ource live nodes
- **L** ... **L**oad nodes
- **I** ... **I**solated nodes (all nodes that are not E, S, L, and all nodes between switches)

The order of the potentials is $E > S > L > I$. I has the lowest potential. $L > I$ means L dominates over I. S dominates over L and I and E dominates over S, L and I. All discovered nodes are evaluated and the node with the highest potential specifies the potential of the hole area. For example, if there are three nodes in the discovered area with the potential I and one with the potential L, then the entire area will be given the potential L. Figure 2.20 shows the graph with node potentials for the substation in

figure 2.18. Safety relevant interlocking decisions for switches can be derived by checking the graph with BFS. This search strategy checks all connected nodes. The highest node potential of each side is stored for further evaluation. To search both sides of the switch separately, the edge of the switch has to be removed from the graph, otherwise the edge would represent a parallel path. If BFS finds a parallel path, then switching is allowed because the nodes are already connected. If no parallel path exists, the potentials on both sides of the switch have to be checked. Potentials of both sides are aggregated in the potential double. For example if one side is isolated and one is live the potential double is "I-S". For each kind of switch the allowed potential doubles are:

- For an earthing switch the potential double I-E is allowed.
- For a circuit breaker the potential doubles I-I, I-L, I-S, L-S, and S-S (if voltages on both sides are synchronous) are allowed.
- For a disconnector the potential doubles I-I, I-L, and I-S are allowed.

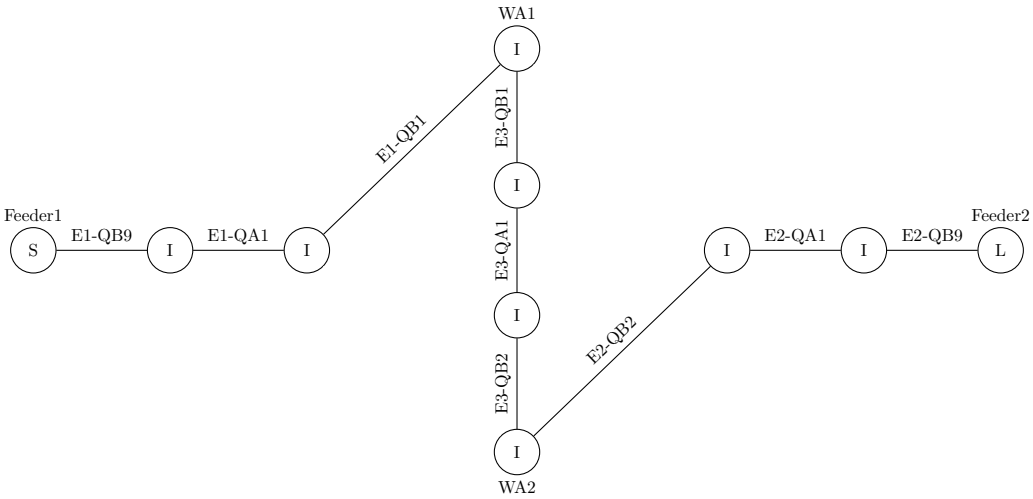


Figure 2.20: Graph of the switchgear in figure 2.12 updated with switch positions as presented in figure 2.18 and node potentials

Some examples are given here, to show how the topology based interlocking works. Starting situation is the switchgear with the given switch positions shown in figure 2.18.

- **Closing the switch E2-QB1** (dotted line in figure 2.21) is allowed because a parallel path to this switch exists. The switches E2-QB2, E3-QB2, E3-QA1 and E3-QB1 (dashed line in figure 2.21) provide this parallel path.

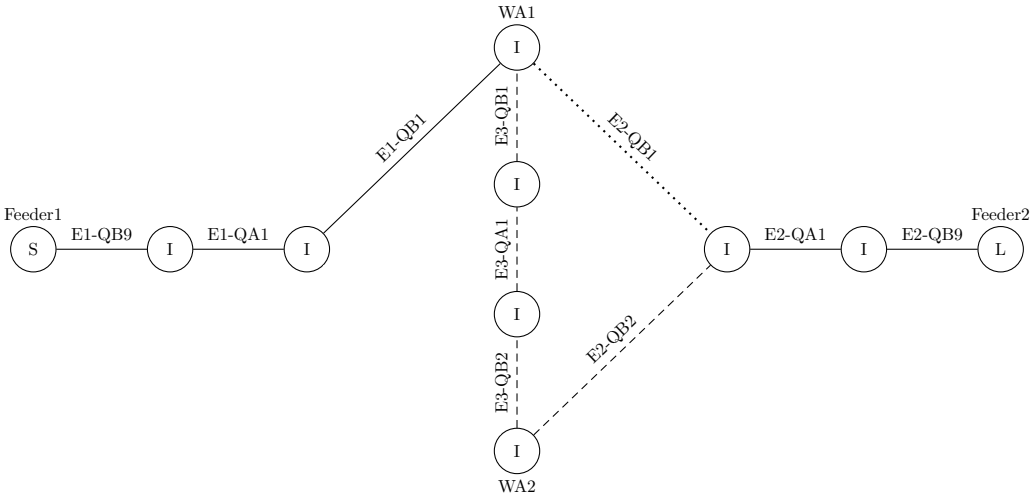


Figure 2.21: Graph of the switchgear in figure 2.12 updated with switch positions as presented in figure 2.18 - Example for enable closing of E2-QB1(dotted line) and switches of parallel path drawn with dashed lines

- **Opening the switch E2-QB2** (dotted line in figure 2.22) is not allowed. The areas and nodes checked with BFS on both sides of the switch (side 1 and side 2) are surrounded by dashed lines in figure 2.22. Side 1 contains nodes with the potentials I and S and in side 2 potentials are I and L. The dominating potentials are S in side 1 and L in side 2. So the potential double is L-S which is not allowed for disconnectors.

- **Opening the switch E2-QA1** (dotted line in figure 2.23) is allowed. The areas and nodes checked with BFS on both sides of the switch (side 1 and side 2) are surrounded by dashed lines in figure 2.23. Side 1 contains nodes with the potentials I and S and in side 2 potentials are I and L. The dominating potentials are here as well S in side 1 and L in side 2. The potential double is L-S which is allowed for the circuit breaker operation and thus an enable signal is generated.

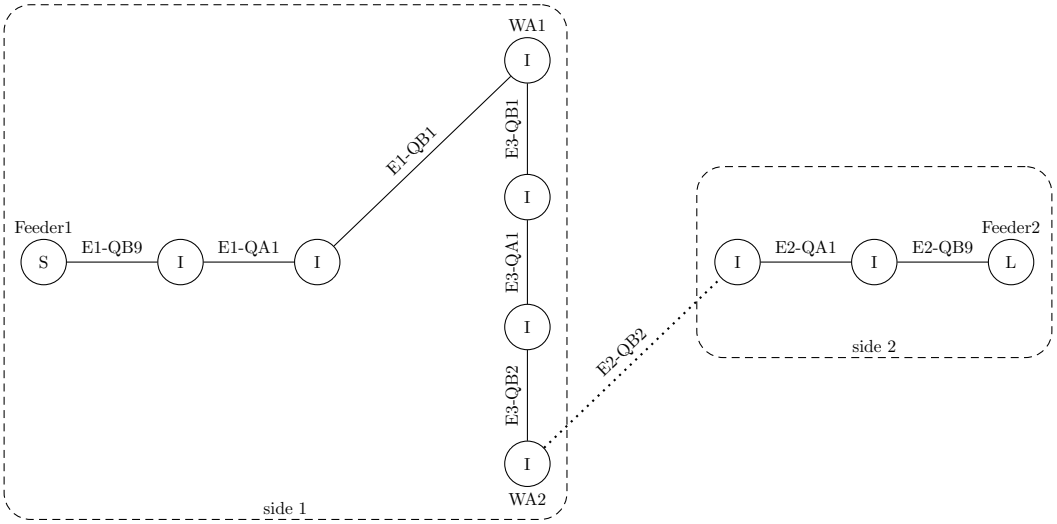


Figure 2.22: Graph of the switchgear in figure 2.12 updated with switch positions as presented in figure 2.18 - Example for interlock opening of E2-QB2(dotted line) framed areas for evaluation of node potential

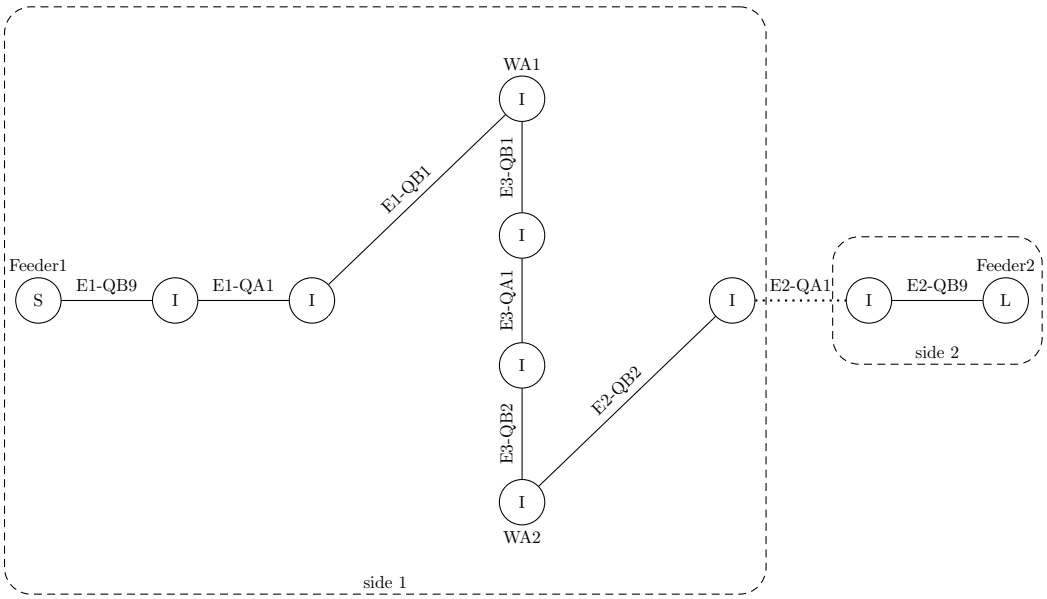


Figure 2.23: Graph of the switchgear in figure 2.12 updated with switch positions as presented in figure 2.18 - Example for enable opening of E2-QA1(dotted line) framed areas for evaluation of node potential

3 State of the Art

This chapter gives an overview on recent research, which has been done on interlocking in substations and points out the problems and improvements with the proposed algorithms for topology based interlocking.

Papers [17], [18] and [19] discuss interlocking and take the topology for interlocking into account and are cited in papers which introduce topology based interlocking. Papers [20] and [21] deliver ideas and solutions for topology based interlocking. The papers [22], [23], [24] and [25] deal with switching sequences based on the topology and handle topology based interlocking. Patents [26] and [27] focuses on safety relevant interlocking based on the topology. Theses [28], [11], [10] and [29] deliver solutions for safety relevant interlocking and for some operational interlocking as well. Thesis [30] presents a simulation tool for IEC 61850 communication and a tool to derive Boolean equations from a topology for safety relevant interlocking.

Interlocking is not only a problem in substations. For example on railway yards interlocking is as well an import issue to prevent train crashes. Papers [31], [32] and [33] show that topology based interlocking is applied in railway yard interlocking.

3.1 Compared Literature

Before computers or microcontrollers were used in substations for automation and control, interlocking was mainly done by mechanic key interlocks. Mechanic key interlocks needed certain keys inserted to operate the switches. For example in a bay the disconnectors adjacent to a circuit breaker can only be operated if the keys were in the locks. After closing the switches the keys could be moved to the circuit breaker to enable clos-

ing the switch. In the close position of the circuit breaker the keys could not be removed to disable operation of the disconnectors under load. This system is rather inflexible and normally only used in single busbar substations. For more complex substations and to increase flexibility, auxiliary contacts of the switches are used to combine switch positions with Boolean operations, to set up electrical circuits to generate enable and interlock signals for electric bolt interlocking. To correctly derive interlock decisions, the following papers introduce algorithms and ideas.

In [17] the problem of "complete" interlocking is discussed. Due to the inflexibility during maintenance with complete interlock, interlock has to be deactivated with the consequence that unorthodox or even unsafe switch operations might occur. Two non operate criteria for disconnectors are defined by the author. Closing the disconnector must not close circuits and opening disconnector must not open circuits. The author shows that the postulated non operating condition for disconnectors is not safe against a failure at the auxiliary contacts or the auxiliary supply applied to electrical interlock circuits. To handle these problems the inversion of the circuits is necessary. In the inverse circuit the closed switches are represented by an open contact and open switches by a closed contact. The proposed interlocking scheme delivers electrical interlock circuits, with a reduced topology, similar to Boolean equations for interlocking. Examples for a double busbar and a ring substation are given to demonstrate the interlocking scheme.

[18] gives an example of the substation of the Dinorwic[8] pumped storage, where the formerly used interlocking is inadequate. Due to operational interlocking and the complexity of the network an other approach to prevent unsafe switch operations is needed. The authors suggest that a "digital approach using Boolean algebra may be suitable". Based on the topology of the substation a node-diagram is set up to find all logic paths. A logic path can be found by starting "at one node of that switch and then trace the succession of nodes from that point to all possible points on the system to which that switch must **not** be connected". With all logic paths for a switch the hard wired circuits can be derived. Topology is used in this paper but only to derive Boolean equations and hard wired circuits for interlocking.

[19] introduces electrical operational interlocks for a fossil-fired power station auxiliary system. This paper deals with the problem that "interlocks are required to restrict the system fault levels to the capacity of the respective circuit-breakers". To have some operational flexibility, it is necessary to take the fault level into account. The authors

[8] located in Great Britain, connected to 400 kV National Grid (UK)

suggest to calculate the fault levels in advance and store them in a table of a microprocessor. This microprocessor further uses logic functions to determine the system configuration and then sums up the effect of all fault sources and generates interlocking decisions.

Paper [20] proposes a topology based interlocking scheme. The topology of the substation is stored in a substation matrix and updated with the state of each switch. An introduced path finding algorithm covers safety relevant switch operation. This algorithm can be used as well to find optimal switch sequences "to minimize switch operations without violating any constraints". That also enables post-fault automatic switching to minimize the effects of the fault and to return quickly to healthy operation. Additionally the surrounding network model is taken into account to avoid any overload situation in the grid. So the authors propose that the algorithm provides interlocking between substations as well.

Paper [21] introduces an approach to decouple interlocking rules and the substation configuration. Boolean rules are related to a substation so the authors propose to realize topology based interlocking in a microprocessor and give rules for switches that are independent of the topology. Therefore a topology recognition algorithm is used to identify switches and other elements in the substation. Rules for switch operation are defined as well to guarantee safe operation which are independent on the topology. To gather a switch decision, an iteration over all connected nodes via neighbour nodes has to be done to identify the status of the substation. Comparisons were done to demonstrate the correct operation of allowed and forbidden switch operations.

Publications [22] and [23] present rules for interlocking and switching schemes for substations that are implemented in a computer. Switching sequences to reconfigure a substation are divided in the papers into tasks like connecting or disconnecting a load or source to the busbar or isolating specific sections of a substation. These tasks are further "split into smaller (elementary) tasks which are performed in a specific order to achieve the desired reconfiguration". If more switch sequences are possible for reconfiguration, then the one with the least switch operations is selected. The proposed program needs as input a matrix representing the topology and limits of the used equipment. General rules of interlocking can be extended in the program with specific interlock rules for the substation. In paper [24] the authors add a graphical user interface to the previously proposed program. Additionally to interlocking and switch sequences the program is able to generate interlock constraints for switches in form of logical expressions.

Paper [25] introduces an expert system to optimize switching sequence in substations. If any equipment is placed in or removed it is necessary to supply all loads. The proposed algorithm evaluates the sequence with the least switching costs, and delivers the optimal path to connect dead nodes with live nodes.

PhD thesis [28] describes how interlock decisions with a process computer are derived, based on node states of the substation. Based on the standards, for different switch types the author derives interlocking rules that are independent of a topology. A process computer evaluates with the topology of a substation the node state of the adjacent nodes and if a parallel path exists, to deliver interlock decisions. That makes the system rather flexible compared to Boolean expressions which are always linked to a topology. The algorithm was compared to Boolean expressions and further tested in an off-line situation for a real substation. One advantage identified by the author is, that the topology based interlocking is able to deliver the reason for interlock to the user, which is not possible with Boolean expressions.

Patents [26] and [27] describe an algorithm for topology based interlocking. The algorithm needs input of switch types, type of nodes, ant the topology that links the nodes and switches. Node potentials are the same as in [11]. The difference is that in the patent [26] it is proposed to use the uncritical potential doubles to disable or enable connection of grounded with isolated areas with a disconnector. Further operational interlocking are possible to be defined with Boolean equations. In patent [27] operational interlocking conditions are presented for normal busbar configurations with auxiliary busbars. But these conditions do not cover all possible configurations for more than two busbars. The proposed search strategy in [27] is similar to a decision tree process applied to each node to identify all parallel paths and nodes.

PhD thesis [11] gives a solution for topology based interlocking. The author proposes that with picture recognition, a single line diagram can be analysed to identify the nodes and switches within the switchgear to set up a node matrix. Further on the nodes are analysed to specify the types of switches not only in circuit breakers and disconnectors, but more in detail - like busbar disconnector, busbar disconnector for coupling bay and so on. As in paper [28] node states on both sides of the switch define the potential double. The potential double or a parallel path to the switch are evaluated with BFS and DFS algorithms to derive interlock decisions. Operational interlocks are discussed as well. Focus lies on auxiliary and transfer busbars and is done by pattern recognition. The idea is to use the sequence of switches found with BFS and DFS to decide if switch

operation is allowed or not. The pattern recognition has to take into consideration sectionalized busbars, which are not easy to handle due to different coupling configurations.

PhD thesis [10] introduces an advisory system for switchgears to support safe switch operations. Besides the simulation of operation generation of switch sequences, a major part is the interlocking system based on topological interlocking. The author proposes that the advisory system can be easily adopted to different switchgears and operational conditions. For operational interlocks "switch classes" and allowed "function paths" have to be defined. Function paths are found with a strategy similar to a decision tree process applied to each node to identify all parallel paths and nodes. Then the topology is needed to generate with all possible switch configurations "enable equations" in form of Boolean equations. Furthermore a check for safety interlocking, based on topological interlocking is done to guarantee safe switch operations only. The Boolean equations are optimized and then prepared for a device.

PhD thesis [29] further develops the proposed algorithms presented in [11] and [10]. The author uses the same pattern recognition and search strategy and presents solutions for operational interlocking. Automatic switching sequences are presented for connecting, disconnecting or earthing feeders. Further the integration of interlocking into a substation control system is shown. Contrary to [11] and [10] the system is not delivering Boolean expressions, used for interlocking but uses topology based interlocking evaluated on a central computer in the substation.

The author presents in [30] a simulation tool for switchgear interlocking in accordance with the standard IEC 61850. It allows to analyse the behaviour of the system, manipulate the system and provides a graphical user interface. Further more a tool is introduced and described, that generates Boolean expressions for safety relevant interlocking, based on the substation topology. Due to the high number of switch combinations the performance of different search strategies is evaluated. Checking all possible switch state combinations generates complete and accurate Boolean equations for interlocking.

3.2 Problems Identified and Improvements

The previous section shows that a lot of problems of topological interlocking have been solved already. But there are still issues to work on which are discussed in this section. First the problem of breadth-first search (BFS) and depth-first search (DFS) finding all parallel paths and then possible improvements for topology based interlocking are listed which define the goals for progress beyond the state of art to be achieved in this thesis.

3.2.1 Finding Parallel Paths for Operational Interlocking

The search strategies BFS and DFS introduced in previous papers, are suitable for safety relevant interlocking, but not for operational interlocking. The algorithms are able to visit each node in a connected area of any graph, so that the node potentials can be evaluated. Besides that, the search strategies can be used to identify if a parallel path exists in the graph. The disadvantage is that BFS and DFS are in general not able to find all parallel paths. This fact does not matter for safety relevant interlocking. For operational interlocking it is not enough to identify, that at least one parallel path exists. For some decisions such as it is necessary to find all relevant parallel paths. For example to check if the busbars are only connected with a coupling switch and no other feeder connects the busbars with disconnectors only. Or with the usage of sectionalizers, couplings and auxiliary busbars to avoid that main busbars are only coupled across the auxiliary busbar, which is not allowed. The following two examples demonstrate why not all parallel paths might be discovered with DFS in a substation. Figure 3.1 shows a double busbar substation[9] with a closed coupling in bay E3, open feeder E2 connected to both busbars and open feeder E1 only connected to busbar WA1. Check for parallel path for switch QB2 in feeder E1 should deliver the two marked paths (dotted line and dashed line) in figure 3.1.
The way the algorithm discovers nodes and edges is:

- Start node for DFS on Side1 of switch E1-QB2 is at busbar WA2.
- In the next steps E2-QB2 and E2-QB1 lead to busbar WA1.
- Further, with switch E1-QB1 Side2 of switch E1-QB2 is reached and a parallel path is found (dotted line).

[9]The given switch positions are unusual but allowed and used here to demonstrate the algorithms

- If at this point not all nodes have been discovered, DFS will go back along the discovered edges to a node where undiscovered edges exist.
- At busbar WA1 the undiscovered disconnector E3-QB1 leads to E3-QA1 and E3-QB2 ending at busbar WA2 - and the algorithm does not detect this path as a parallel path because it does not end at Side2 of switch E1-QB2.
- At that point all edges have been marked as seen.

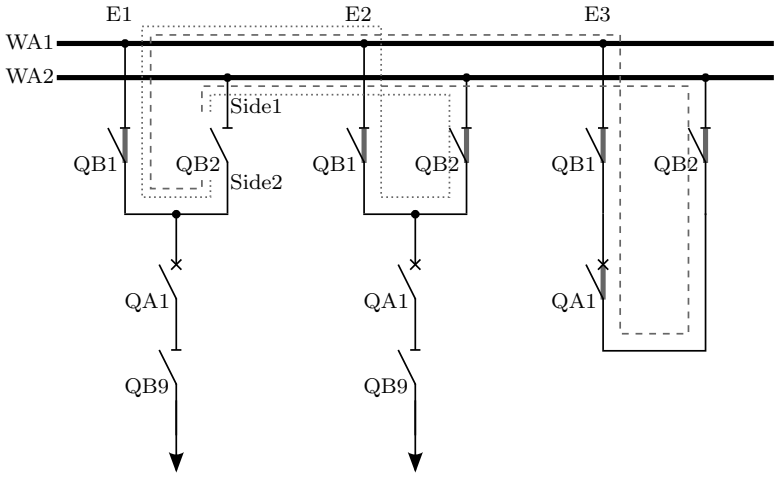


Figure 3.1: Example of a substation configuration in which DFS will most likely not identify all parallel path

In this specific case starting the search on Side2 of switch E1-QB2 would deliver following sequence:

- Discover E1-QB1 and find the busbar WA1.
- In next steps E2-QB1 and E2-QB2 lead to WA2 which is the other side of switch E1-QB2 and so marked as the first parallel path (dotted line).
- Again going back to undiscovered edges leads to WA1.
- At this point E3-QB1, E3-QA1 and E3-QB2 lead to busbar WA2 and so this path is now marked as the second parallel path (dashed line). At this point the algorithm found successful both parallel paths.

However, to start on the other side only works in this configuration. If for example a sectionalizer is installed in a substation, then BFS or DFS will not find all parallel paths. An example is given in figure 3.2. The configuration is similar to the one in figure 3.1 but the parallel paths cross the sectionalizers of the busbars.

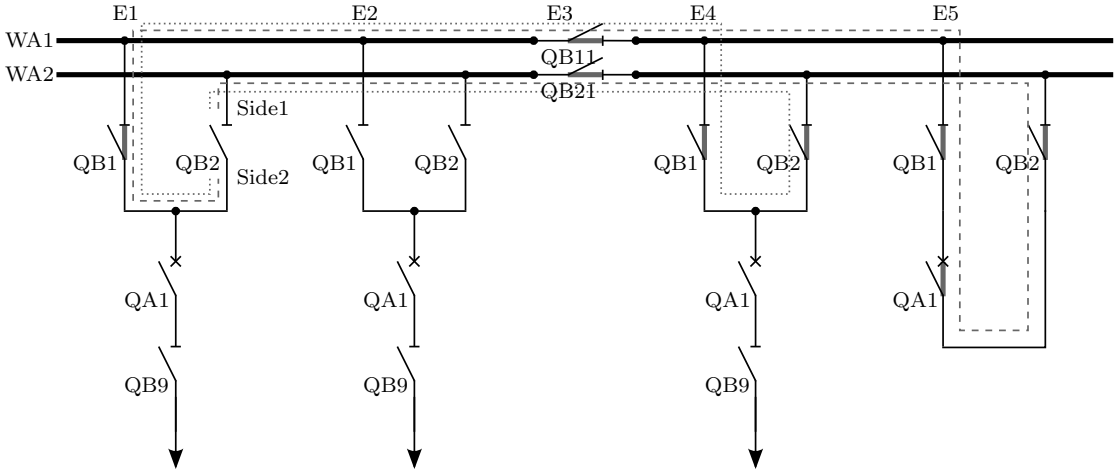


Figure 3.2: Example of a substation configuration with sectionalized busbars where DFS might not identify all parallel path

Starting on Side1 did not work for the previous configuration and does not work for this as well. So the description is not presented here. To demonstrate that in this case, starting on Side2 of switch E1-QB2 does not find all parallel paths, the results of DFS are presented in the following sequence:

- Switch E1-QB1 leads to the first section of busbar WA1.
- Switch E3-QB11 leads to the second section of busbar WA1.
- After crossing E4-QB1 and E4-QB2 the second section of busbar WA2 is discovered.
- Along E3-QB21 first section of WA2 is reached and one parallel path is found (dotted line).
- Going back to undiscovered edges leads to the second section of busbar WA2.
- E5-QB2, E5-QA1 and E5-QB1 lead to the second section of busbar WA1 and the second parallel path is not found - due to the sectionalizers.

The conclusion is that, if on only one side of the switch is another switch that is part of all possible parallel paths, then starting DFS from both sides delivers all parallel paths. But the DFS search strategy is not able to find all parallel paths if other switches that are part of the parallel paths are at either side of the switch. When the search strategy is adopted to the specific design of a substation, it is still possible to find all relevant parallel paths with DFS. The solution is presented in chapter 4.4. Compared to that, the proposed algorithm in [27] and [29] searches the edges multiple times and needs more computation power.

3.2.2 Improvement Potential

The papers presented give solutions for working topology based interlocking but there is still potential for improvement. The following points show problems and deficits, for which solutions are presented in this thesis in chapter 4 and 5.

- **No redundancy:** All proposed solutions for topology based interlocking are designed to run on a central device. This means that there is no redundancy if only one such central device exists. A failure on the central device leads to unsafe and uninterlocked switch operations. Increasing redundancy can be reached by installing an additional device or by decentralization. New bay controllers with protection functions can be used to provide decentralized interlocking.

- **No standardized description of the substation:** None of the papers used a standard to describe the substation. The papers proposed manual input of the topology or an automatic topology recognition by scanning a picture. Testing algorithms are introduced to ensure a correct interpretation of the topology. Standard IEC 61850 defines how to describe the substations topology, which can be used for topology based interlocking.

- **No automatic configuration of substation communication:** An important point for topology based interlocking is to keep the configuration of the substation current and communicate, enable or interlock signals for safe operation. Manually configured proprietary solutions to update the configuration are prone to errors. For that point as well standard IEC 61850 provides solutions, so that it is possible to set up the exchange of switch positions automatically.

- **No reduced topology:** In the case of a central unit that searches the topology, the entire topology has to be taken into account. But in the case of decentralization, it is possible to reduce the topology so, that only the necessary switches are taken into account for interlocking decisions. This is similar to the Boolean expressions where only the needed switch positions are linked in the Boolean equations. On the one hand it is possible to reduce computation time because search algorithms have to analyse less nodes and edges. On the other hand, not all switch positions are needed to be transmitted to all other devices so that the load on the communication bus is kept on a low level.

- **Search strategy:** The previous section showed that BFS and DFS have problems finding all parallel paths. [29] proposed another search strategy to find all parallel paths in a substation. The disadvantage with this algorithm is that the computation time is high due to the fact that edges are handled multiple times to find all parallel paths. If BFS and DFS are adopted to meet the requirements in a substation, as described in this thesis, it is possible to find all parallel paths without handling edges multiple times.

4 New Methods

This chapter presents new methods to enable and improve topology based interlocking. Section 4.1 introduces how the switchgear type can be detected automatically. Criteria for the substations are defined and explained with examples for normal and modified configurations.

Section 4.2 introduces new properties for nodes and edges. Further potentials are needed for nodes to enable a proper detection of the switch type and for operational interlocking decisions. Network groups are introduced to group feeders in a substation to allow or prevent the connection between certain feeders for operational reasons. For edges, the adaptation of length for longitudinal coupling is introduced to use the length of the parallel path as criterion for interlocking decisions.

Automatic detection of switches is introduced in section 4.3. Therefore, different types of switches are introduced and discussed for the different substation configurations. For each type of substation, an example is given to present the switch types.

Modified search algorithms are presented in section 4.4. Modifications are introduced for breadth-first search (BFS) and depth-first search (DFS). The strategies are adopted to the topology of a substation to solve the problems identified in chapter 3.

4.1 Automatic Detection of the Switchgear Type

In section 2.1.3 different types of substations are introduced. For the functions and improvements presented in the following section, it is necessary to know the type of substation, for example to identify the function of a switch. Figure 4.1 shows a double busbar with an auxiliary busbar. Switch E1-QB7 in bay E1, which is surrounded by

a dashed line, is connected to a feeder on one side and to a busbar on the other side. Figure 4.2 shows a ring busbar. Switch E1-QB9 in bay E1, which is marked with a dashed line, is also connected on one side to a feeder and to a busbar on the other side. In both cases the switch has in the same type of adjacent nodes for identification, but different functions.

- For example in a double busbar with an auxiliary busbar configuration, this type of switch is a bypass switch, which is only allowed to switch if a parallel path exists.
- For a ring busbar configuration the switch is a line disconnector, which in general has no parallel path.

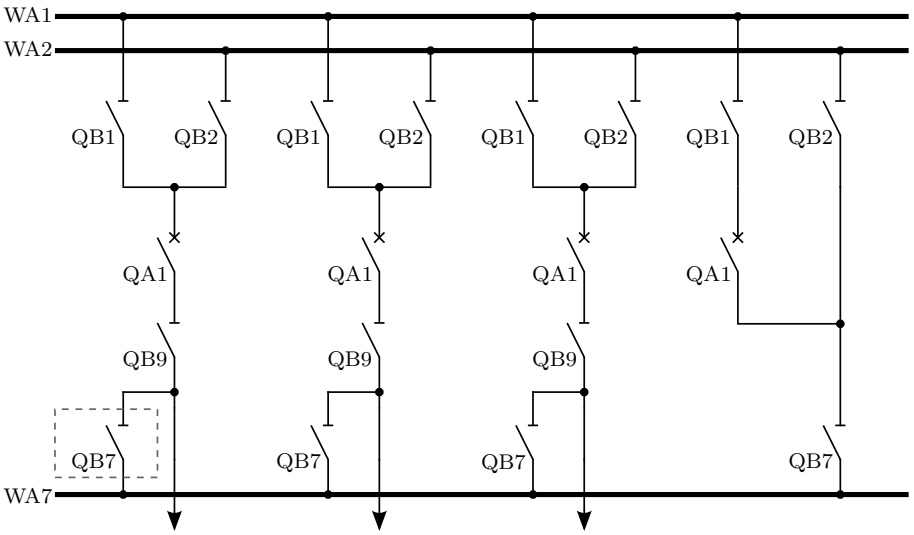


Figure 4.1: Double busbar with auxiliary busbar - bypass switch E1-QB7 is marked

This is the reason why it is necessary to know the type of substation to automatically detect the switches and use this information for interlocking decisions. Typical substations can be clustered in four types:

- substations with normal busbar
- substations with ring busbar
- substations with 1 ½-breaker method
- substations with 2-breaker method

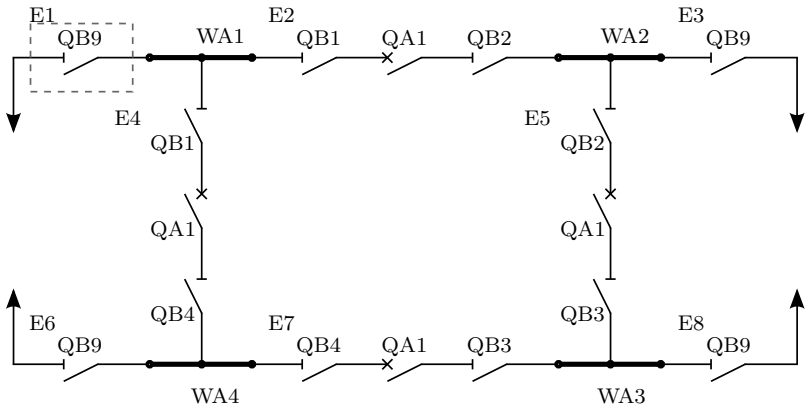


Figure 4.2: Ring busbar - line disconnector E1-QB9 is marked

The category **normal busbars** includes the configurations single, double and triple/-multiple busbar, with or without auxiliary busbars. These configurations have a similar structure and the same switch types so that they can be subsumed to one category.
There are some criteria that can be used to differentiate the types of substations. Table 4.1 shows values to identify the type of substation. The five used criteria are:

A: the number of switches on the shortest path from a load to a busbar. Figure 4.3 shows for a double busbar for feeder E1. The two possible connections from the load to the busbar are marked with the dashed line. Each path includes three switches, so criterion A is equal to three.

B: the number of switches on the shortest path between busbars in a feeder bay. The dotted line in figure 4.3 shows the connection of two busbars with two switches in feeder E2. Therefore B is equal to two.

C: the number of switches on the shortest path between busbars in a coupling bay. The dash dotted line in bay E4 of figure 4.3 shows this path passing three switches, so C is equal to three. For normal busbar configurations values form one (a sectionalizer only) to three (like coupling E4 presented in figure 4.3) are possible, depending on the coupling.

D: the number of loads and sources connected to a busbar. For the example given in figure 4.3 D is equal to three.

E: the number of busbars. The given example has two busbars, so E is equal to two.

A "-" indicates that this connection does normally not exist in that substation configuration. For example, the single busbar configuration can not couple busbars in a bay as there is only one busbar. "2+" indicates that at least two loads / sources are connected to a busbar. "*F" is equal to the number of feeders in the configuration.
Earthing switches are ignored because they do not influence the criterion. Furthermore they do not provide any additional information to identify the substation type.

Table 4.1: Criteria to differentiate between types of substations

substation type	A	B	C	D	E
single busbar	3	-	1-3	2+	1
..with auxiliary busbar	1	4	1-3	2+	2
double busbar	3	2	1-3	2+	2
..with auxiliary busbar	1	2	1-3	2+	3
..with shunt disconnector	2	2	1-3	2+	2
triple busbar	3	2	1-3	2+	3
ring busbar	1	-	3	1	*F
1 ½-breaker method	3	9	-	2+	2
2-breaker method	3	6	3	2+	2

A... number of switches on the shortest path from a load to a busbar

B... number of switches on the shortest path between busbars in a feeder bay

C... number of switches on the shortest path between busbars in a coupling bay

D... number of loads/sources connected to a busbar

E... number of busbars

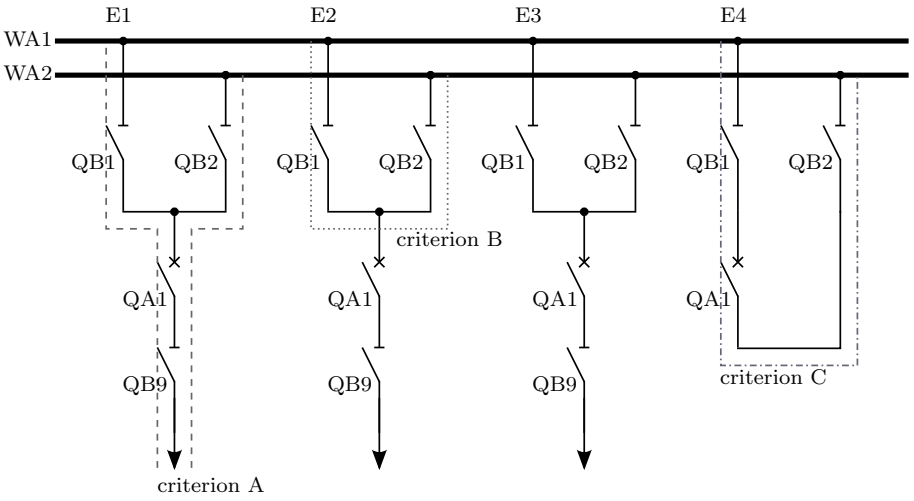
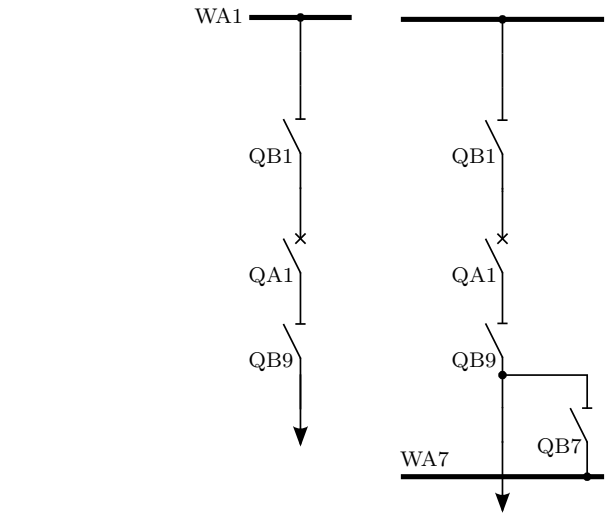


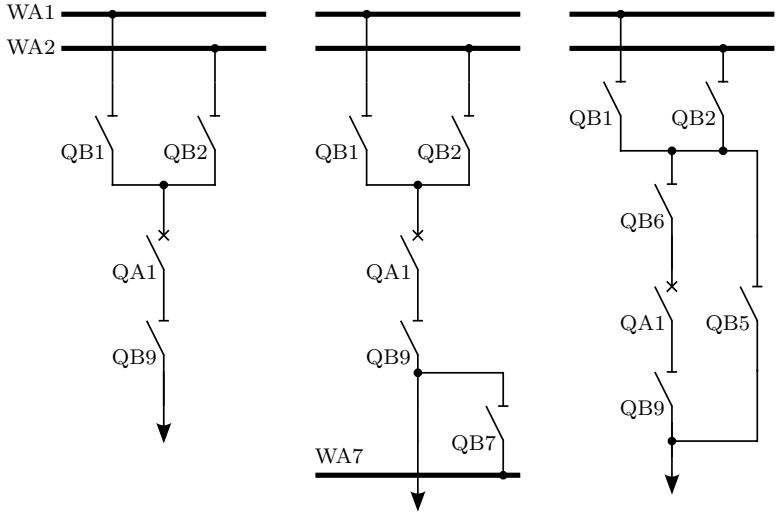
Figure 4.3: Double busbar to show criteria A, B and C

- The category **normal busbar** subsumes different configurations. Figure 4.4 shows bays of single busbar, double busbar, double busbar with auxiliary busbar, and double busbar with shunt disconnector configurations. These configurations are all very different so that it is not possible to identify a normal busbar with only one criterion. But there are additional possibilities to check the configuration. **Criteria A, B and E** can be used to identify the different substation types subsumed in the category normal busbar.
  - A single busbar bay is shown in figure 4.4(a). This configuration is the only one with a single busbar, so that criterion E allows a unique identification (criterion E equals one). An exception is the special configuration of the 1 ½-breaker method given in figure 4.6(e). In this example, the bay of the 1 ½-breaker method is connected to the same busbar twice so that criterion B is equal to nine. For the single busbar configuration no path exists.
  - A single busbar with an auxiliary busbar needs other criteria. An example of such a bay configuration with a single busbar and an auxiliary busbar is presented in figure 4.4(b). With criterion A equal to one and criterion B equal to four this topology can be detected as well.
  - A double busbar bay is shown in figure 4.4(c). A common property of double and multiple busbar configurations is the shortest distance of two switches between the two busbars. So criterion B is equal to two. The number of busbars can be evaluated by counting the number of connections from the load to the busbars.
  - The existence of an auxiliary busbar in a double busbar configuration can be detected with criterion A equal to one, similar to the single busbar. Counting the number of connections from the load to the busbar with the length of one the numbers of auxiliary busbars, and with the length of 3 the number of busbars, can be evaluated. An example of a double busbar with an auxiliary busbar is given in figure 4.4(d).
  - Criterion A equal to two, then a shunt disconnector as shown in 4.4(e) is used.



(a) single busbar bay

(b) single busbar bay with auxiliary busbar



(c) double busbar bay

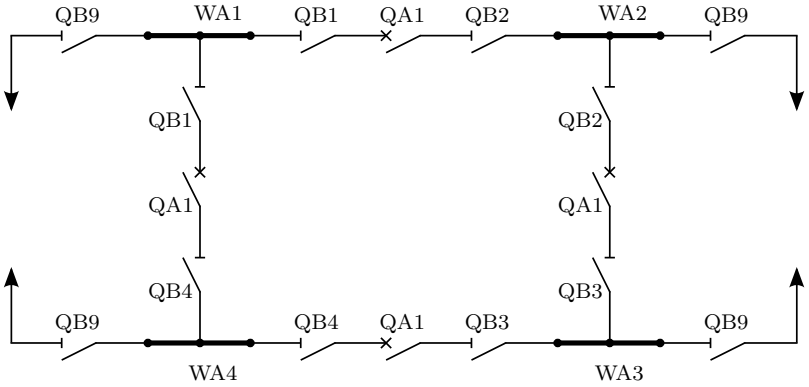
(d) double busbar bay with auxiliary busbar

(e) double busbar bay with shunt disconnector

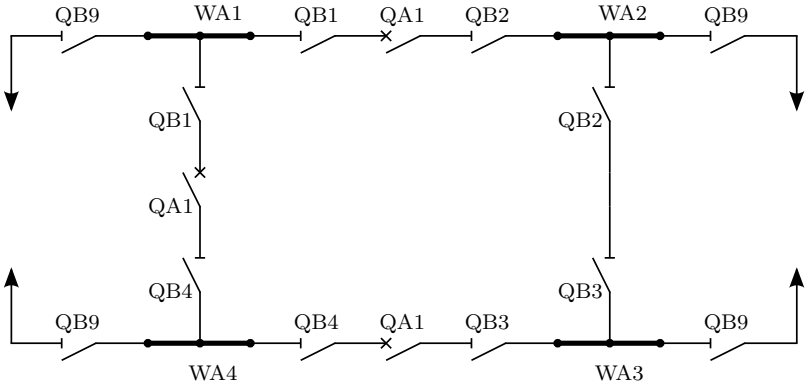
Figure 4.4: Example bays for single and double busbar configurations

- With **criterion D** a **ring busbar** can be identified. To identify the special configurations criterion C is used. This is the only configuration that has a separate busbar for each feeder (criterion D = 1). As shown in figure 4.5(a), the feeders are only connected to the busbar with a disconnector. The coupling switches are needed to connect or disconnect the feeders from each other. That means, to connect or disconnect a feeder one or two circuit breakers are operated, depending on the configuration. So for each feeder, a busbar and a coupling bay is needed. Therefore, the number of feeders is equal to the number of busbars and the number of coupling bays. This can be used as additional criterion. A special configuration of a ring busbar is given in figure 4.5(b). One coupling bay has no circuit breaker (coupling between busbars WA2 and WA3). This means that opening and closing the disconnectors in that bay is only possible if a at least one side is isolated or a parallel path exists. Figure 4.5(c) shows another special configuration. Criterion D is still 1. The difference is that two sources are connected with circuit breakers. The couplings have only one disconnector and loads are directly connected to the busbar. Due to this construction, reconfiguration is only possible if the sources are switched off. Both configurations need no adaptation for interlocking. Furthermore these configurations are detectable by checking the number of switches between busbars in coupling bays (criterion C).

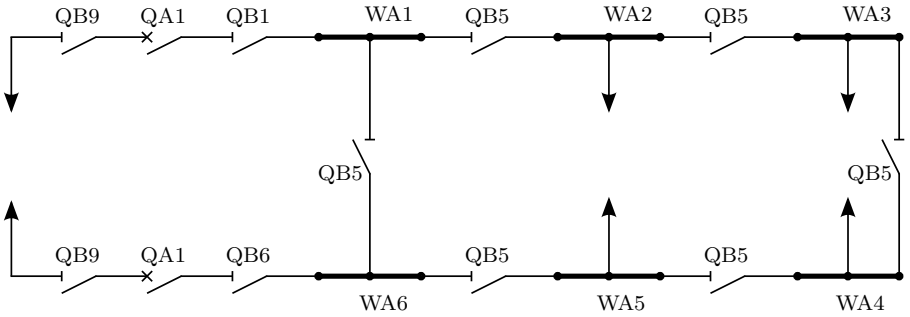
- **Criterion B** is suitable for the **1 ½-breaker method**. The 1 ½-breaker method has normally no explicit coupling so the decision can include criterion C. Due to the topology of the bays it is possible to couple the busbars with a circuit breaker in a bay with feeders. Figure 4.6(a) shows that this construction has nine switches (criterion B = 9) between the busbars. This information can be used for unique identification. Figure 4.6(a) shows a bay of a 1 ½-breaker configuration. Normally, a 1 ½-breaker configuration has some of these bays. Figure 4.6(b) shows a possible configuration with an explicit coupling for the busbars. This coupling bay can be identified as coupling bay and does not influence the evaluation of the shortest path between the busbars for feeders (criterion B). A configuration given in 4.6(c) will not influence criteria B as well, as no connection exists between the two busbars. Figure 4.6(d) shows a configuration of a bay that could be a bay of a 2-breaker configuration as well. If all other bays in the substation fulfill criterion B, a warning for this bay should be signaled to check the validity for the substation.



(a) normal ring busbar



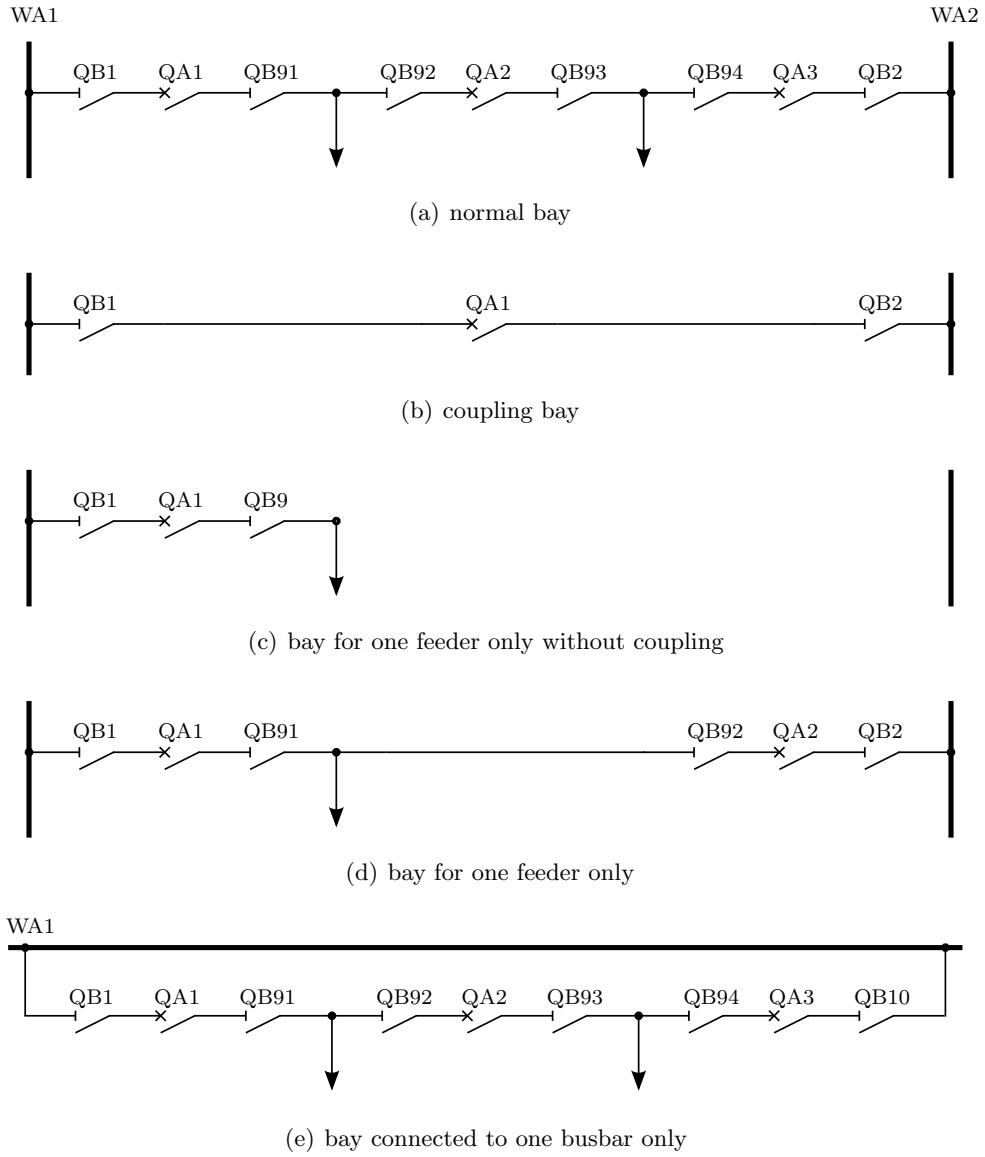
(b) special configuration, a coupling bay without circuit breaker



(c) special configuration, a coupling bay without circuit breaker

Figure 4.5: Example for normal and two special ring busbar configurations

Figure 4.6(e) shows a configuration that is connected to only a single busbar, but does not influence criterion B. All these special configurations work with the same topology based interlocking rules for the 1 ½-breaker method so that these special configurations do not require any adaptations.



(a) normal bay

(b) coupling bay

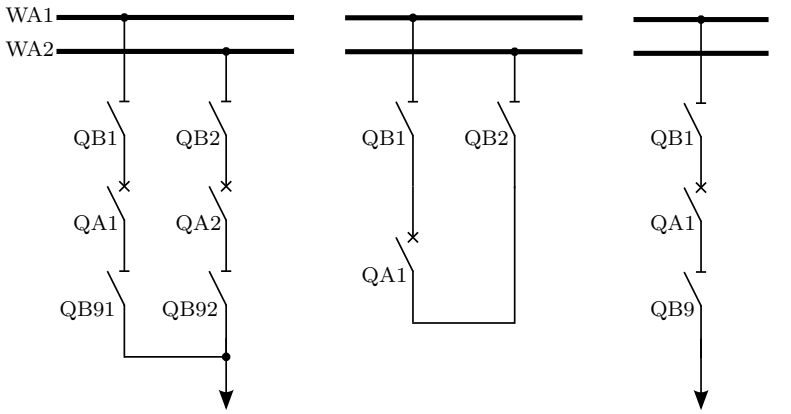
(c) bay for one feeder only without coupling

(d) bay for one feeder only

(e) bay connected to one busbar only

Figure 4.6: Examples of normal bay configuration and four unusual configurations of a 1 ½-breaker method configuration

- **Criterion B** is suitable for the **2-breaker method**. The 2-breaker method has normally several feeders like the ones presented in figure 4.7(a) and one explicit coupling as shown in figure 4.7(b). If the circuit breaker in the feeder bays are not designed to connected two busbars then an extra coupling is necessary. Figure 4.7(a) shows that six switches connect two busbars. So criterion B equal to six can be used for unique identification for the 2-breaker method. Due to maintenance a feeder might only be connected to one busbar as presented in figure 4.7(c). This configuration does not influence criterion B. A detection is possible because the feeder bay does not connect two busbars.



(a) normal feeder bay (b) coupling bay (c) feeder connected to only one busbar

Figure 4.7: Examples of a feeder bay, a coupling bay and an unusual configuration of 2-breaker method configuration

As one can see, the different substation types can be identify by analysing the feeder bays. The defined criteria in this section are sufficient for unique and automatical identification of the substation type.

4.2 New Node and Switch Properties

In this section, for operational interlocking and to identify the switch type new node potentials are introduced. Furthermore an additional property of nodes - the network group - is proposed that allows to group loads, sources and transformers for operational

reasons. With the network group it is possible to prevent or allow connections between feeders.

4.2.1 New Node Potential

For topology based interlocking following node potentials were already introduced in section 2.3.5:

- **E** ... **e**arth nodes
- **S** ... **s**ource live nodes
- **L** ... **l**oad nodes
- **I** ... **i**solated nodes

To identify the switches and for the operational interlocking like "Keep the switching sequence" and "Do not allow to energize a transformer with a disconnector" additional node potentials are needed. Therefore the following potentials are introduced:

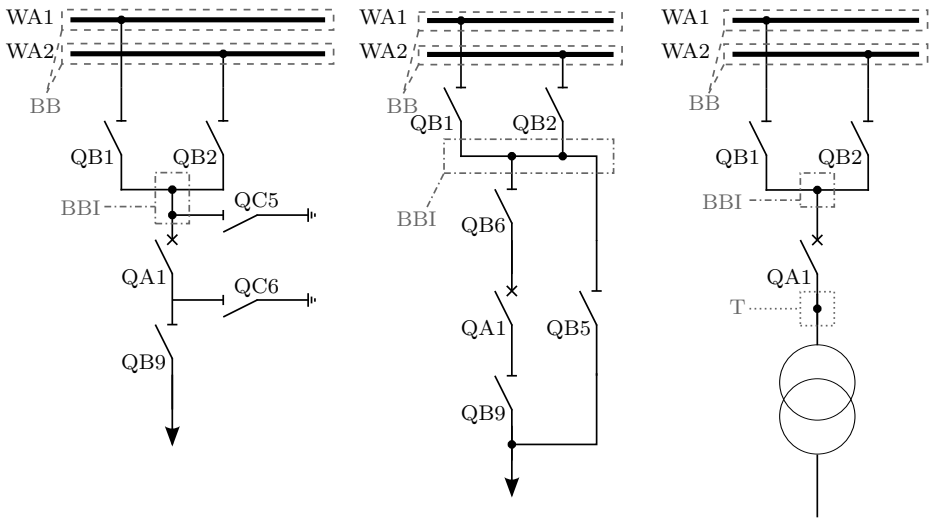
- **BB** ... **b**us**b**ar nodes
- **T** ... nodes of a **t**ransformer
- **BBI** ... **i**solated nodes that are separated with a disconnector from the **b**us**b**ar in a feeder bay

Potentials "BB" and "T" are used to identify switches and for operational interlocking. The node potential "BBI" is only needed to identify certain switches and is not used for topology based interlocking. Figure 4.8 gives examples in which the new node potentials are marked.
Nodes with the potential:

- BB are marked with dashed lines in figures 4.8.
- T is marked with dotted line in figure 4.8(c)
- BBI is marked with dash dotted lines in figures 4.8.

The potential "BBI" is needed to differentiate between the two switches QC5 and QC6 in figure 4.8(a) because for the reduced topology introduced in 5.2 the state of switch

QC5 is needed in other bays but QC6 is not needed. In figure 4.8(b) the potential is needed to identify switch QB5, a shunt disconnector, and differentiate it from QB9, a feeder disconnector. After finishing the identification of switches, node potential "BBI" is set back to the potential I. The order of the potentials for topology based interlocking is: $E > S > L > BB > T > I$. I is the lowest potential. $T > I$ means T dominates over I. BB dominates over T and I, and so on. E has the highest potential and dominates over S, L, I, BB, T and I. The interlocking conditions are discussed in chapter 5.



(a) Double busbar bay

(b) Double busbar bay with a shunt disconnector

(c) Double busbar bay with a transformer

Figure 4.8: Example bay configuration for double busbar configurations to show the new node potentials

4.2.2 Network Group

Network groups are used in electric grids to group lines, loads or parts of the grid. The reasons for doing that are:

- Obtain clarity in the grid.
- Prevent coupling of asynchronous parts.
- Keep short circuit current within rated limits for the circuit breakers.
- Prevent overloading of any device.

In previous proposed topology based interlocking solutions, network groups are not taken into account. So it is not possible to prevent connections between feeders. Boolean equations provide the function but the formulation of these conditions gets very complex, especially for larger substations. To use network groups for topology based interlocking an additional and new property for nodes besides the node potential is proposed in this thesis - **the network group**. To enable high flexibility following new solution is proposed:

A "default" network group is used for each node as long as no other group is selected. Isolated, busbar and earth nodes will always have the default group. Load, source and transformer nodes can be specified with a group. For evaluation with search strategies a specified group node always dominates the default group node. So it is possible to connect feeders with the default group to any other feeder but prevent a connection of feeders that are of different none default network groups. For example in a substation with four feeders, feeder 1 has network group 1, feeder 2 has network group 2, feeders 3 and 4 are default. Then it is allowed to connect feeder 3 and 4 with feeder 1 or 2, but it is not possible to connect feeder 1 with feeder 2.

4.2.3 Length of Switch

In chapter 5 topology based interlocking is introduced. Interlock and enable signals are derived for the case that no parallel path exists, due to the potential doubles for a switch. If a parallel path exists, the length of this path is needed to identify the configuration and derive correct enable or interlock signals. The length of a parallel path is equal to the sum of the lengths of the switches on the path. Therefore it is necessary to define the length of each switch. The default value for the length of a switch is one, so that the length of the parallel path is equivalent to the number of switches on it. But for switches that couple sections of the same busbar (e.g. sectionalizers) the length has to be set to zero. The reason for that adaptation is explained with the following example. Figures 4.9, 4.10 and 4.11 show a double busbar configuration [10] with sectionalized busbars, two coupling bays and one feeder in each section of the busbars. For closed switches the length of each switch is presented in brackets close to the label. In all three figures feeders E1 and E3 are connected to busbar WA1. The busbars are coupled

[10] A double busbar configuration will most likely not have two feeders connected in such a way in a real substation, but to demonstrate the problem, the configuration is reduced to a minimum of needed switches.

and the sections are connected. If feeder E1 or E3 is supposed to be switched to the other busbar, the existence of a parallel path for switches E1-QB2 or E3-QB2 has to be checked. In all configurations a parallel path exists for switches E1-QB2 and E3-QB3, but has different length. The parallel paths for switch E1-QB2 are marked with dash dotted lines, and the parallel paths for switch E3-QB2 with dashed lines.

- **Example 1:** In figure 4.9, the coupling in bay E4 connects both busbars and switches E2-QB11 and E2-QB21 in coupling E2 connect the busbar sections. For switch E3-QB2, the parallel path passes four switches: E3-QB1, E4-QB1, E4-QA1 and E4-QB2. For switch E1-QB2, the parallel path passes six switches: E1-QB1, E2-QB11, E4-QB1, E4-QA1, E4-QB2 and E2-QB21.

- **Example 2:** In figure 4.10, the coupling in bay E4 connects both busbars and switches E2-QB11 and E2-QB20, E2-QA1 and E2-QB2 in coupling E2 connect the busbar sections. For switch E3-QB2, the parallel path passes four switches: E3-QB1, E4-QB1, E4-QA1 and E4-QB2 like in example 1. For switch E1-QB2, the parallel path passes now eight switches: E1-QB1, E2-QB11, E4-QB1, E4-QA1, E4-QB2, E2-QB20, E2-QA1 and E2-QB2.

- **Example 3:** In figure 4.11 coupling E4 is not closed. The sections of the busbars are connected with E2-QB11 and E2-QB21. Coupling busbars WA1 and WA2 is done with switches E2-QB10, E2-QA1 and E2-QB2. The parallel path for switch E3-QB2 passes five switches: E3-QB1, E2-QB10, E2-QA1, E2-QB2 and E2-QB21. For switch E1-QB2 the parallel path has five switches as well: E1-QB1, E2-QB11, E2-QB10, E2-QA1 and E2-QB2.

To define a unique criterion for the length of parallel path for busbar coupling, it is necessary not to count switches that are part of longitudinal coupling. This means the switch length needs to be adopted for:

- **Example 1:** Length of switches E2-QB11 and E2-QB21 have to be set to zero. All other switches have the length of one. This results in a length of the parallel path for switch E3-QB2 of four, and for switch E1-QB2 of four.

- **Example 2:** Length of switches E2-QB11, E2-QB2, E2-QA1 and E2-QB20 has to be set to zero. All other switches have the length of one. In this case the parallel paths for switches E3-QB2 and E1-QB2 have the length of four.

- **Example 3:** Length of switches E2-QB11 and E2-QB21 have to be set to zero. All other switches have the length of one. Again the parallel paths for switches E3-QB2 and E1-QB2 have the length of four.

Setting the length for longitudinal coupling to zero guarantees to identify the same length of parallel paths. For sectionalizers, the length can always be set to zero because they can only be used as longitudinal coupling switches. Switches E2-QB1, E2-QB2, E2-QA1, E2-QB10 and E2-QB20 need an adaptation of the length depending on the switch positions. If the switches are used for longitudinal coupling as in example 2, then the length has to be set to zero. But if the switches are used for transversal coupling as in example 3, then the length has be set to one. So it is necessary to update the length of coupling switches before search strategies are analysing the topology. The length can be set automatically by analysing the busbars sections the coupling is connected to. A longitudinal coupling connects different sections of the same busbar. So it is possible to check with BFS if a coupling switch is part of a coupling that connects different sections of the same busbar. If so, the length of the couplings switches has to be set to zero, otherwise the length of the coupling switches have to be set to one.

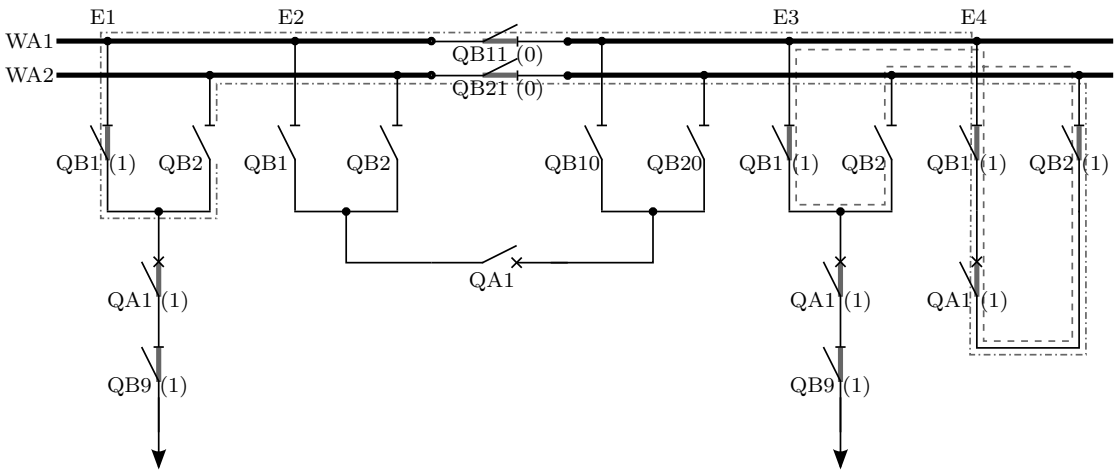


Figure 4.9: Example 1 of a double busbar substation to demonstrate the effect of longitudinal coupling on the length of the parallel path - length of closed switches is added to the switches in brackets

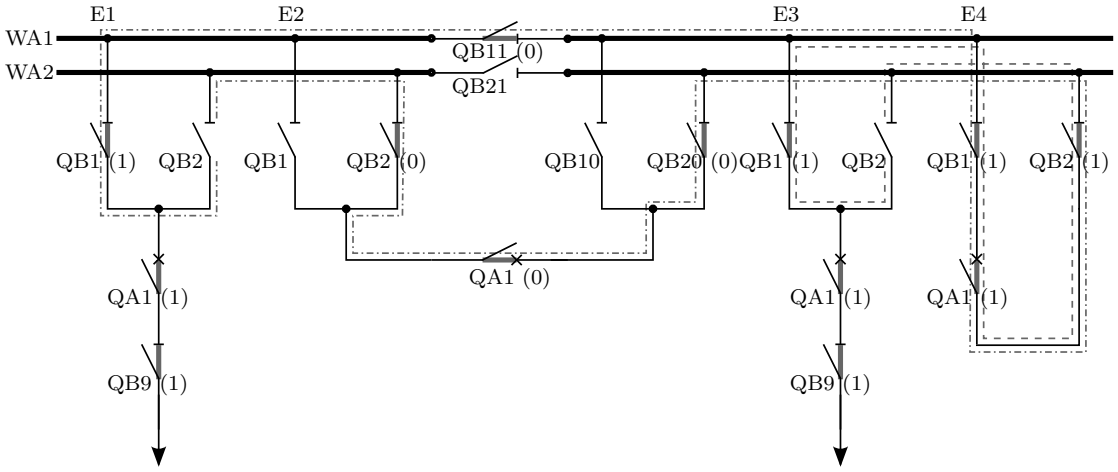


Figure 4.10: Example 2 of a double busbar substation to demonstrate the effect of longitudinal coupling on the length of the parallel path - length of closed switches is added to the switches in brackets

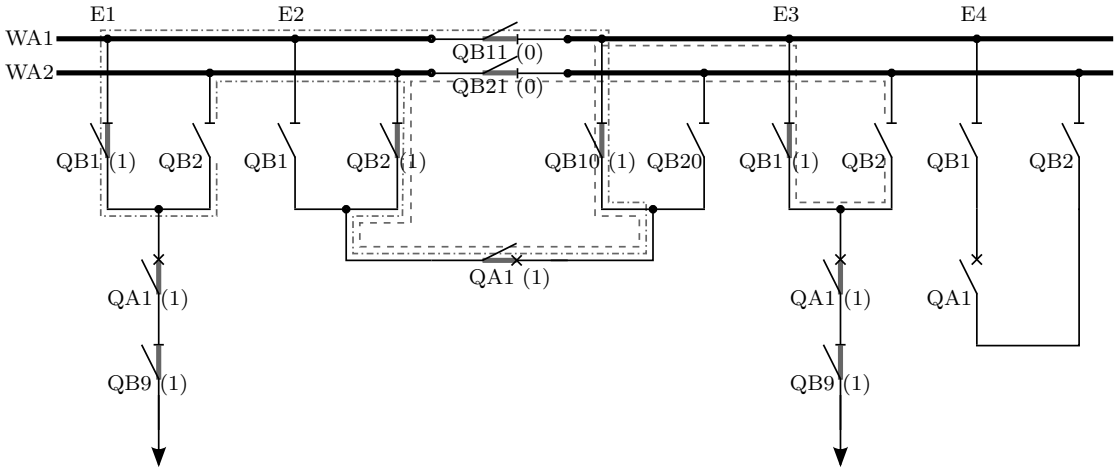


Figure 4.11: Example 3 of a double busbar substation to demonstrate the effect of longitudinal and transversal coupling on the length of the parallel path - length of closed switches is added to the switches in brackets

4.3 Automatic Detection of the Switch Type

Operational interlocking decisions strongly depend on the position of the switch inside of the switchgear. Therefore it is necessary to further differentiate for the circuit breakers and disconnectors. To reduce errors due to wrong manual input, automatic detection of switches can be effective. Switches can be clustered based on the type of bay. Following bays are possible:

- Feeder bay
- Transformer bay
- Coupling bay

In a feeder bay switches have other restrictions than in a coupling bay. The type of bay can be identified by checking if any load or source is connected to the bay. If a load or source is detected in the bay, it is a feeder bay. In the case that a transformer is in the bay, it is a transformer bay. If none of that is in the bay then it is a coupling bay. Inside a bay the switches can be further identified in detail, by analysing one or both connection points (e.g. connected to a load or a busbar). The type of switch depends on the type of substation as well. Therefore the types of switches are discussed in this section. The different types of switches and rules to automatically detect them are introduced. Then examples with figures for each substation type, defined in 4.1, are given. The corresponding interlocking decisions are discussed in 5.1

4.3.1 Types of Switches

Circuit breakers are used to change power flow by switching current. Circuit breakers are differentiated for interlocking decisions due to the bay they are installed in.

- circuit breaker in a feeder bay (CBR-F)
- circuit breaker in a transformer bay (CBR-T)
- circuit breaker in a coupling bay (CBR-C)

Interlocking decisions of disconnectors do not only depend on the bay they are installed. Disconnectors are used for different purposes, so that there are more types to differen-

tiate. In a coupling bay the following types can be differentiated by checking the nodes they are connected to:

- disconnector in a coupling bay adjacent to a busbar (DIS-C-BB) - only one side is connected to a busbar
- disconnector in a coupling bay used as sectionalizer (DIS-C-S) - both sides of this switch are connected to the same busbar, but different sections.
- disconnector in a coupling bay not fitting in any other specification (DIS-C) - any other disconnector in a coupling bay with no connection to a busbar.

Disconnectors in a feeder bay are differentiated between:

- disconnector in a feeder bay adjacent to a busbar (DIS-F-BB) - disconnector that is connected to a busbar on one side
- disconnector in a feeder bay used as bypass switch (DIS-F-Y) - disconnector that is connected to a busbar on one side and connected to a feeder on the other side. For ring busbars this criterion is not used so that such a switch is detected as DIS-F-BB. This is necessary because DIS-F-Ys are only allowed to be operated if a parallel path exists. In a ring busbar this switch has in general no parallel path. Therefore the switch is identified in a ring busbar as DIS-F-BB.
- disconnector in a feeder bay used as shunt disconnector (DIS-F-SD) - disconnector that is connected to a feeder on one side and to the isolated node of a DIS-F-BB on the other side
- disconnector in a feeder bay used as cross-tie disconnector (DIS-F-CT) - disconnector that connects two different bays.
- disconnector in a feeder bay not fitting in any other specification (DIS-F) - any other disconnector in a feeder bay
- disconnector in a transformer bay adjacent to a busbar (DIS-T-BB) - disconnector in a transformer bay with one side connected to a busbar
- disconnector in a transformer bay (DIS-T) - any other disconnector in a transformer bay.

Earthing switches are always grounded on one side. But earthing switches can as well be differentiated due to their position and adjacent node.

- earthing switch in a feeder bay adjacent to a DIS-F-BB (DIS-E-FG) - this switch has to be identified to transmit its state to know if the bay is grounded or not, in the case that the operational interlocking rule "forward earth potential with disconnectors" is activated.
- earthing switch adjacent to a line, load or source (DIS-E-L) - this switch is used to ground lines, cables or sources. For safe operation it is necessary to have the information if the line or source is isolated or grounded.
- earthing switch in a feeder bay (DIS-E-F)
- earthing switch in a transformer bay (DIS-E-T)
- earthing switch in a coupling bay (DIS-E-C)
- earthing switch adjacent to a busbar (DIS-E-BB)

4.3.2 Switch Types of Normal Busbar Configurations

Normal busbar configuration includes the configurations single busbar, double busbar and triple/multiple busbar, with or without auxiliary busbars and all busbars can have one or more sections. The example in figure 4.12 shows a double busbar configuration with earthing switches. In normal operation each feeder is connected to only one busbar. When the busbars are coupled then the feeders can switch without interruption from on to another busbar. Bypass switches or shunt disconnectors can be used to bypass the circuit breaker for maintenance. The switches in feeder bays E1 and E2 for the example given in figure 4.12 are:

- CBR-F for circuit breakers QA1
- DIS-F-BB for disconnectors QB1 and QB2
- DIS-F for disconnectors QB9
- DIS-E-FG for earthing switches QC5
- DIS-E-F for earthing switches QC6

- DIS-E-L for earthing switches QC9

The switches in the coupling bays can be identified as:

- CBR-C for circuit breaker QA1
- DIS-C-BB for disconnectors QB1 and QB2
- DIS-E-C for disconnectors QC5 and QC6
- DIS-E-BB for disconnectors QC11 and QC21

Figure 4.13 shows configurations of a cross-tie switch, a bypass switch and a shunt disconnector. Earthing switches are left out in these examples to not overload the figures.

- DIS-F-CT for QB5 in figure 4.13(a)
- DIS-F-Y for QB7 in figure 4.13(b)
- DIS-F-SD for QB5 in figure 4.13(c)

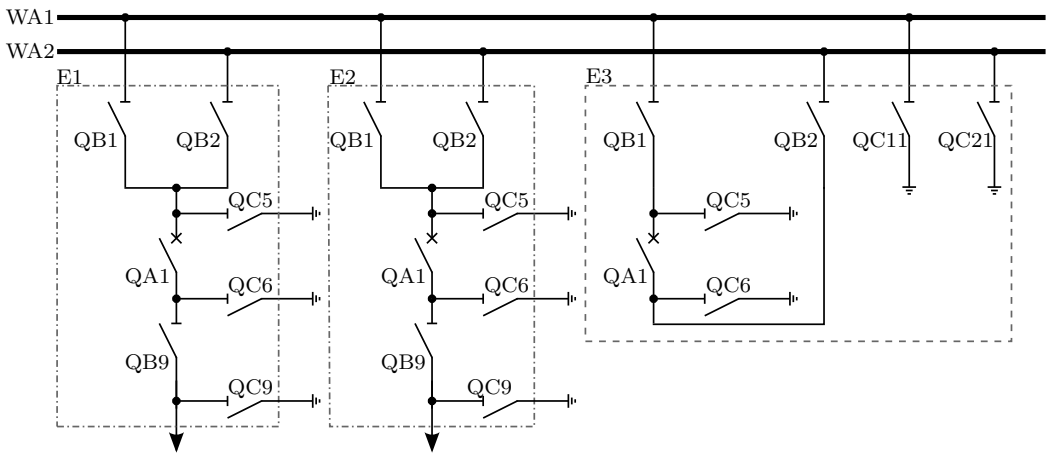
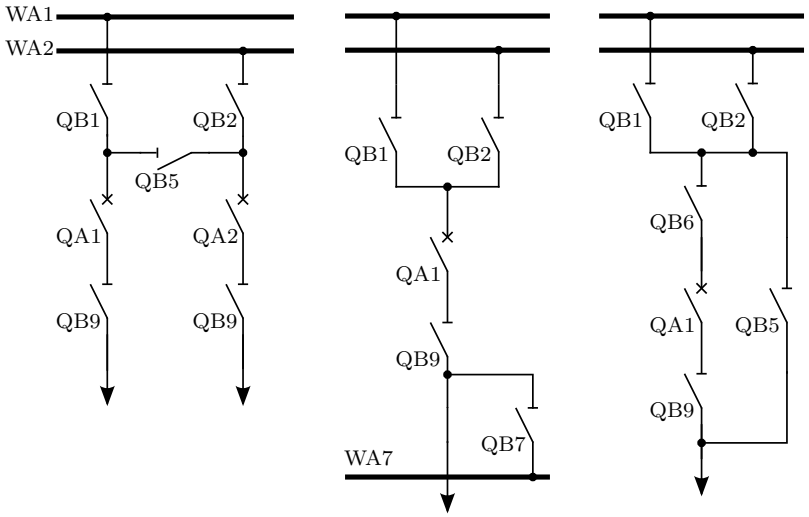


Figure 4.12: Double busbar with marked bays and earthing switches



(a) bay with cross-tie switch (b) bay with auxiliary busbar (c) bay with shunt disconnector

Figure 4.13: Example bay configuration of a cross-tie switch, a bypass switch and a shunt disconnector

4.3.3 Switch Types of Ring Busbar Configurations

A ring busbar has rather simple feeders. They are normally only connected with a disconnector to a busbar. Disconnectors are not allowed to switch current. Therefore each feeder needs a separate busbar. Coupling bays are then needed to connect and disconnect feeders. An example for a ring busbar with four feeders and all possible earthing switches is presented in figure 4.14. Feeder bays are framed with dash-dotted lines and coupling bays are framed with dashed lines. E1, E2, E3 and E4 are feeder bays and E5, E6, E7 and E8 are coupling bays. The switches in the feeder bays for the ring busbar example given in figure 4.14 can be identified as:

- DIS-F-BB for disconnectors QB9
- DIS-E-FG for earthing switches QC9
- DIS-E-BB for earthing switches QC11, QC21, QC31 and QC41

The switches in the coupling bays can be identified as:

- DIS-C-BB for disconnectors QB1, QB2, QB3 and QB4

- CBR-C for circuit breakers QA1, QA2, QA3 and QA4
- DIS-E-C for earthing switches QC5 and QC6

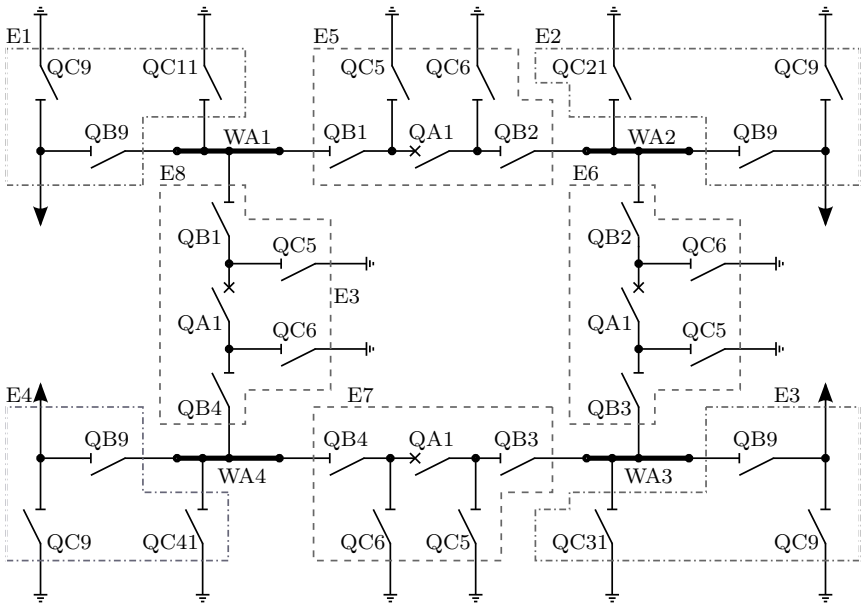


Figure 4.14: Ring busbar with marked bays and earthing switches

4.3.4 Switch Types of 1 ½-Breaker Method Configurations

The 1 ½-breaker method normally has no coupling. Coupling of the busbars can be done with the circuit breakers in the feeder bays. Each bay has three circuit breakers for two feeders. So it is possible to connect the feeders without interruption to one busbar each, or both to the same busbar or even couple the busbars within the bay. This configuration has only a few types of switches for feeder bays. The switches in the feeder bay E1, E2 and E3 of figure 4.15 can be identified as:

- CBR-F for circuit breakers QA1, QA2 and QA3
- DIS-F-BB for disconnectors QB1 and QB2
- DIS-F for disconnectors QB91, QB92, QB93 and QB94
- DIS-E-FG for earthing switch QC1 and QC6

- DIS-E-L earthing switch QC91, QC92
- DIS-E-BB for earthing switches QC11 and QC21
- DIS-E-F for earthing switches QC2, QC3, QC4, QC5

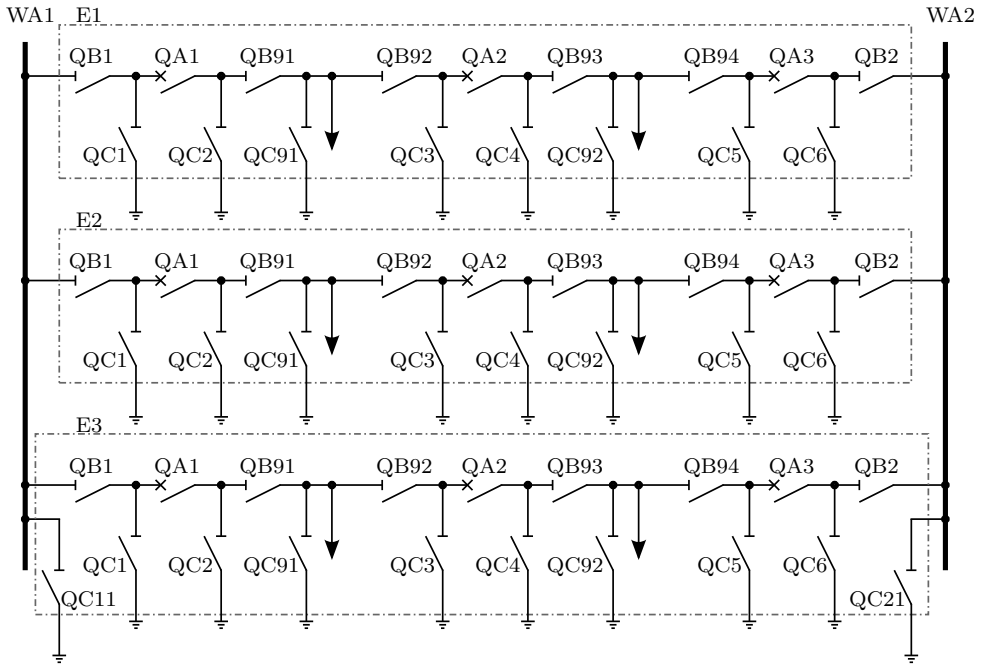


Figure 4.15: 1 ½-breaker method with marked bays and earthing switches

4.3.5 Switch Types of 2-Breaker Method Configurations

A 2-breaker busbar is given in figure 4.16. Two feeder bays E1 and E2 are connected to two busbars WA1 and WA2. If the switches QA1 and QA2 are designed to switch the feeders on and off, but are not capable to switch and carry the currents that occur during normal operation when they are used for busbar coupling, then a coupling bay E3 is needed to enable the transfer of a feeder from one to the other busbar without interruption. The switches in the feeder bay E1 and E2 of figure 4.16 can be identified as:

- CBR-F for circuit breakers QA1 and QA2
- DIS-F-BB for disconnectors QB1 and QB2

- DIS-F for disconnectors QB91 and QB92
- DIS-E-FG for earthing switches QC1 and QC2
- DIS-E-F for earthing switches QC3 and QC4
- DIS-E-L for earthing switch QC9

The switches in the coupling bay E3 of figure 4.16 can be identified as:

- DIS-C-BB for disconnectors QB1 and QB2
- CBR-C for circuit breakers QA1
- DIS-E-C for earthing switches QC1 and QC2
- DIS-E-BB for earthing switches QC11 and QC21

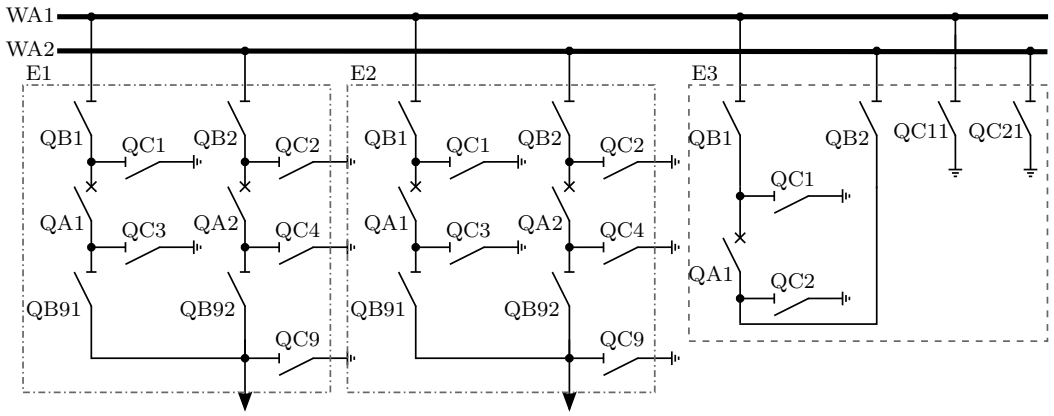


Figure 4.16: 2-breaker method with marked bays and earthing switches

4.4 Modified Search Strategy

4.4.1 Breadth-First Search

The search strategy breadth-first search (BFS) can be used to identify the node potentials on both sides of a switch. This strategy works for any configuration of the substation. Additionally, BFS provides the information of the shortest connection between two nodes if such a path exists in the graph. Therefore, the edges must not be weighted [14, p. 158]. This means that each edge equally increases the distance from the starting node. But in the previous section 4.2.3 different switch lengths have been introduced. In order to continue using BFS some adaptations are required to still discover the shortest path with BFS between two nodes for correct and unique interlocking decisions.

The flow chart for BFS without modifications is given in figure 8.1. Figure 4.17 shows the flow chart of the modified BFS. The gray filled objects are new, and the one filled with a gray line pattern is modified.

The new node properties introduced in section 4.2 need to be taken into account with BFS. Therefore the modification “evaluate node properties” is introduced. This subsumes following adaptations for the topology based interlocking:

- Check the node potential and evaluate the highest discovered potential in the searched area as return value.
- Check the network group. Return the specified network group that is found or return default if no specified network group is found.
- Evaluate the distance from the start node to the new node. The distance for the new node is calculated by adding the length of the discovered edge to the distance of the actual node.
- If finding a switch in fault position, then return that one switch in fault position is found for further evaluation.
- If finding an earth node, set the potential to earth because it is the highest possible potential. Do not mark this node as discovered and do not add it to the list. This is necessary because all earthing switches are connected to one earth node and earthed areas would otherwise appear as connected areas.

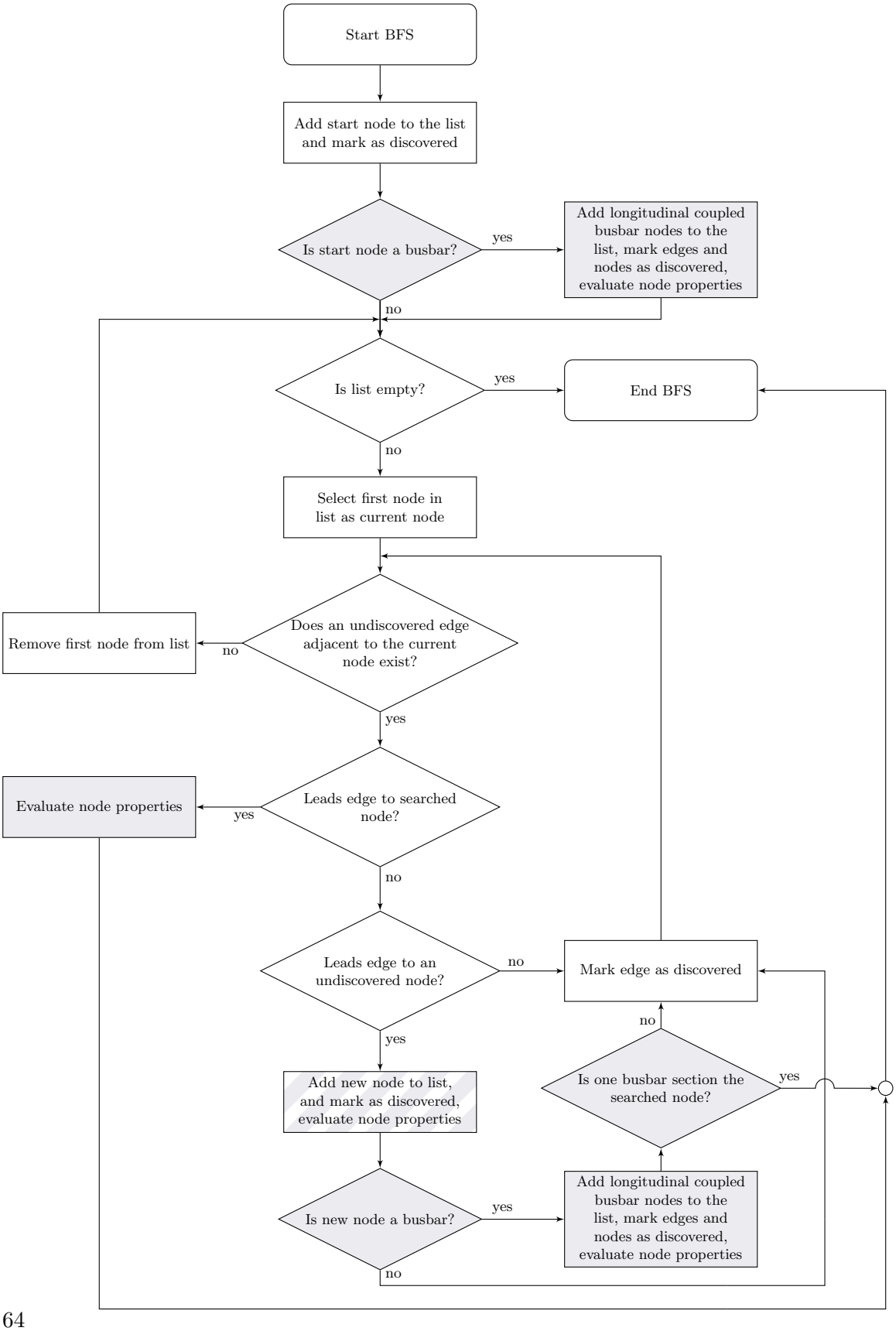


Figure 4.17: Flowchart for the modified breadth-first search

To allow using BFS to find the shortest parallel path in a substation with weighted edges adaptations are needed. The new proposed solution lets longitudinal coupled busbars appear as a single node to BFS, so that only edges with the length of one remain in the substation graph. Figure 4.18 shows a double busbar configuration with longitudinal coupled busbars. For the unmodified BFS this configuration results in a graph presented in figure 4.18. If the unmodified BFS is used to find the shortest parallel path for switch E3-QB2, then the path marked with the dashed line will be identified. This path has a length of four. The path marked with the dotted line has a length of three, but passes five switches. Two of the switches have a length of zero and therefore this path is not identified as shortest path with the unmodified BFS.

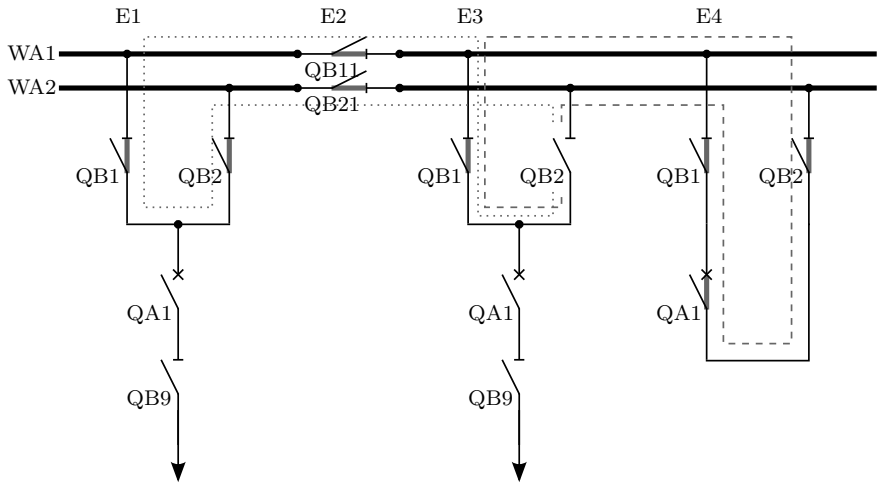


Figure 4.18: Example substation configuration to discuss needed modifications for BFS

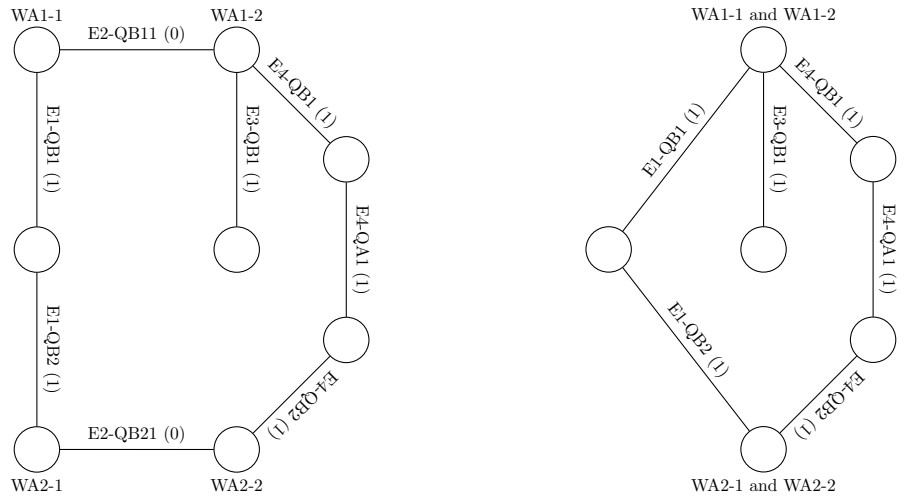
Figure 4.19(b) shows how the graph of the substation configuration in figure 4.18 is interpreted by the proposed modified BFS. The longitudinal coupled busbars are interpreted as a single node. So it is possible that BFS identifies the shortest parallel path, because as shown in figure 4.19(b) only switches with a length of one are in the graph.

Therefore it is proposed in this thesis to check with BFS for new discovered nodes and for the start node, if it is a busbar. If so then the new modified algorithm has to:

- Search for all longitudinal coupled busbars by checking for closed switches with the length of zero.
- If any longitudinal coupled busbars are found, then the longitudinal coupling

switches have to be marked as discovered and the found busbars have to be added to the list and need to be marked as discovered.

- Check, if any of the found busbar sections is the searched node.



(a) Graph for normal BFS

(b) Graph for modified BFS

Figure 4.19: Example for the appearance of the graph of the substation presented in figure 4.18 for normal and modified BFS, length of switches is added to each switch in brackets

This adaptation guarantees that longitudinal coupled busbars are handled like a single node. All other switches have the same length and therefore BFS is able to deliver the shortest path for interlocking decisions with this modification.
Information needed for BFS:

- Adjacency list of the substation
- Current switch positions
- Length of switches
- Node potentials and network groups
- Start node (one side of the switch)
- Searched node (other side of the switch)

Return values of BFS:

- The existence of a parallel path.
- If a parallel path exits, the length of the shortest path between start and end.
- If no parallel path exists:
  - Highest potential connected to the start node
  - The evaluated network group.
- Information if a switch in fault position is detected in the searched area.

4.4.2 Depth-First Search

The search strategy DFS is used for the identification of parallel paths. The problem is that this strategy does not find all relevant parallel paths in a substation, which is discussed in section 3.2.1. Adaptations that make it possible to use DFS to find all relevant paths for topology based interlocking are proposed in this section.

The flow chart for DFS without modifications is given in figure 8.2. Figure 4.22 shows the flow chart of the proposed modified DFS finding all relevant paths in a substation. The new proposed steps in the flow chart are filled with gray colour and modified objects are filled with gray line pattern. Following example presents how the new elements and the modification change the search strategy.

Figure 4.20 presents a double busbar configuration. Figure 4.21(a) shows how the substation graph is interpreted by the unmodified DFS. The unmodified DFS finds only one of the two parallel paths, marked with the dashed and dotted line, for switch E1-QB2. The reason why the unmodified DFS does not find both parallel path is because both parallel paths are passing switch E2-QB21 adjacent to the start node and switches E1-QB1 and E2-QB11 adjacent to the goal node.

To identify all relevant parallel paths it is proposed to search for the next busbar adjacent to the start node with BFS and then for longitudinal coupled busbars sections as proposed for BFS to use all connected busbar sections as start node. For the goal node the next adjacent busbar needs to be searched as well and with the longitudinal coupled busbars sections these coupled busbar sections are then used as goal nodes. These modifications ensure to find all relevant parallel paths with DFS. Starting and ending DFS between two busbars guarantees to find all relevant parallel paths, because

parallel paths possible in feeder bays and coupling bays are then directly linked to the start and end node. Figure 4.21(b) shows how the substation graph is interpreted by the modified DFS. Busbar sections WA2-1 and WA2-2 are interpreted as start node and busbar sections WA1-1 and WA1-2 are now interpreted as goal node and edge E1-QB1 is discovered on the way to the goal node.

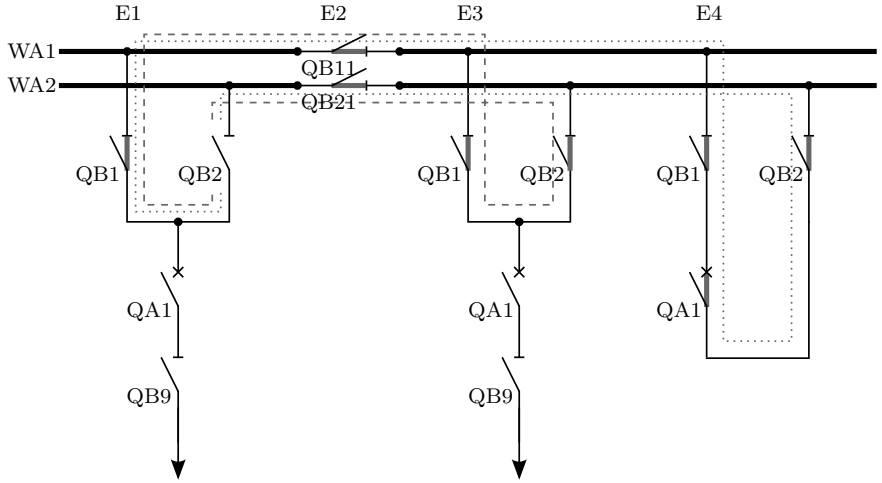
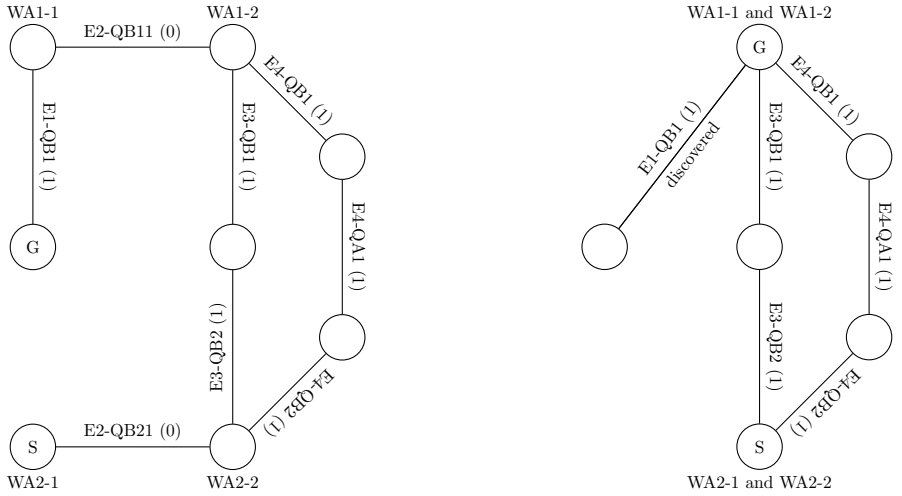


Figure 4.20: Example substation configuration to discuss needed modifications for DFS

Therefore it is proposed in this thesis that before DFS starts to search the graph it is necessary to:

- Search for the next adjacent busbar of the start node. Check further for longitudinal coupled busbars. Use the found busbars as new start nodes. Mark the found nodes and edges as discovered and add the new nodes to the stack. Evaluate the length of the path from the old start node to the new start nodes.
- For the searched node (equal to the other side of the switch) it is necessary as well to identify the next adjacent busbar. The busbar and longitudinal coupled busbars are then used as new searched nodes. But these new nodes are not put onto the stack and not marked as visited, only the edges leading to the new nodes are marked as visited. The length from the searched node to the new searched nodes has to be evaluated to provide the correct length for operational interlocking decisions.



(a) Graph for normal DFS

(b) Graph for modified DFS

Figure 4.21: Example for the appearance of the graph of the substation presented in figure 4.20 for normal and modified DFS, "S" marks the start node and "G" marks the goal node

Further adaptations are proposed to provide the length of paths and to find all relevant parallel paths:

- If one of the searched nodes is found, then the algorithm has to calculate the length of the path for the return value.
- The algorithm has to continue searching for further undiscovered edges and must not stop searching and mark the edge as discovered.

As for BFS every discovered node has to be evaluated for the node properties. The difference is that node potential and network group are not necessary to be checked because DFS is used if a parallel path exists and the nodes are already connected. The following properties for nodes are still needed for DFS:

- Evaluate the distance for the new node to the start node. The distance for the new node is calculated by adding the length of the discovered edge to the distance of the actual node.
- If finding a switch in fault position this property has to be stored for the parallel path it appears in, including the index of the fault switch.

- If a node with earth potential is discovered do not mark this node as discovered and do not add it to the list. This is necessary because all earthing switches are connected to one earth node and earthed areas would otherwise appear as connected areas.

With these adaptations it is possible to find all relevant paths. A further discussion on theoretical configurations where this strategy does not work is done in chapter 6. Chapter 6 also presents as well algorithms to test a graph if the search strategy is valid and can be used for topology based interlocking. Information needed for the modified DFS is similar to the modified BFS:

- Adjacency list of the substation
- Current switch positions
- Length of switches
- Node potentials and network groups are not needed as this options are not evaluated
- Start node (one side of the switch)
- Searched node (other side of the switch)

Return values of the modified DFS are:

- Number of parallel paths found
- Length for each parallel path
- Fault status for each parallel path, including the index of the fault switch.

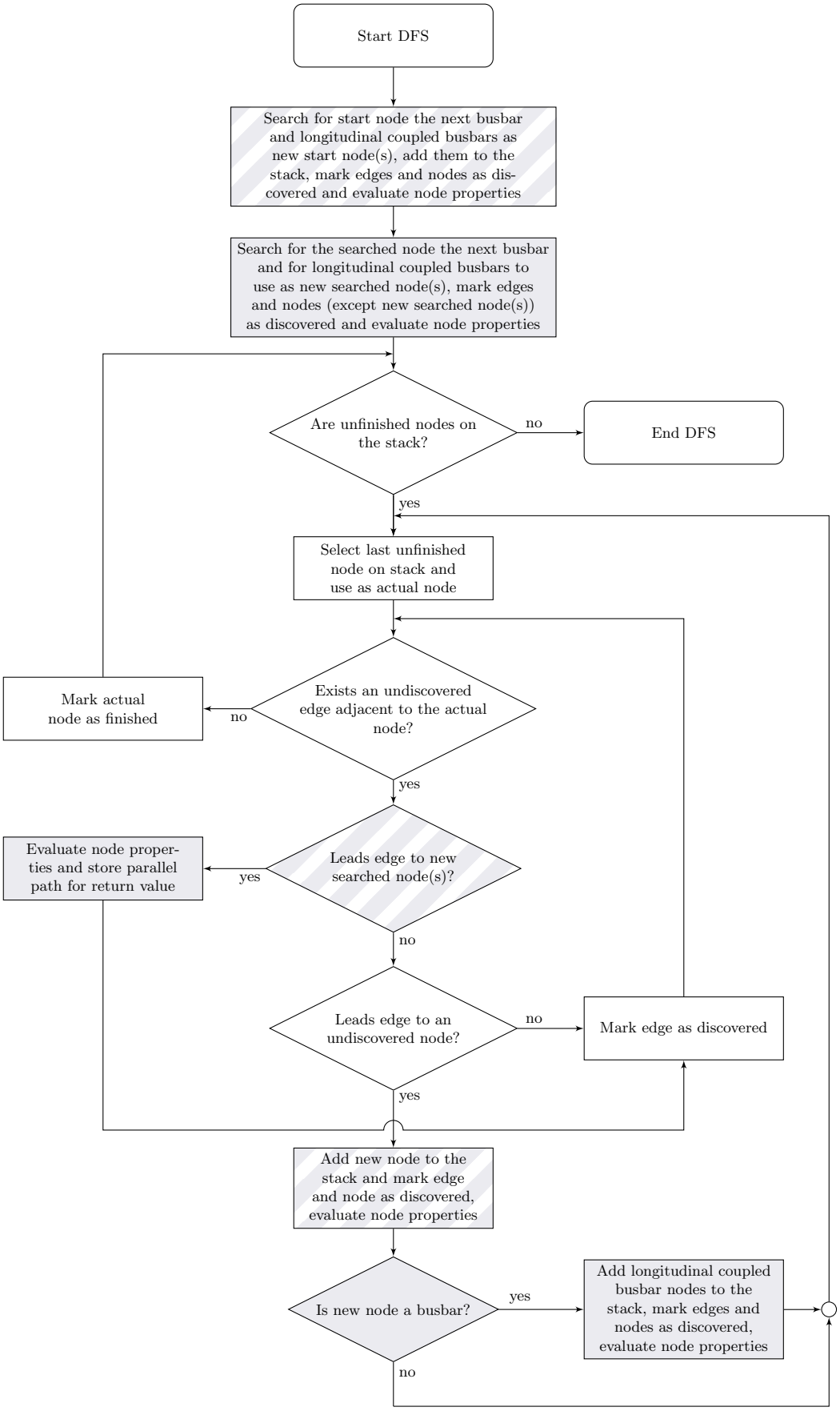


Figure 4.22: Flowchart for the modified depth-first search

5

Topology Based Interlocking

Interlocking is needed in switchgears to ensure safe operation of switches. Section 5.1 presents topology based interlocking. As described in 2.2, interlocking can be divided into two categories:

- Safety relevant interlocking, to allow only safe switch operation that does not endanger any persons or equipment in or around the substation. The rules needed for safety relevant interlocking are discussed in section 5.1.2. The rules are defined based on the capability of the switches and are independent on the configuration.
- Operational interlocking restricts switch operations, which would be enabled by safety relevant interlocking, due to operational reasons. General rules are described in section 5.1.3. Operational interlocking defined for different substation configurations is described in sections 5.1.4 to 5.1.8.

Switches in fault position must not be stressed. Topology based rules for switches in fault position are discussed in section 5.1.9. These rules provide compared to Boolean equations still interlocked switch operation even if switches in fault position are detected.

Section 5.2 proposes solutions to reduce the topology in order to increase performance of topology based interlocking. Depending on the configuration it is possible to reduce the topology by fifty percent. The advantages are listed and the needed switches are defined and presented with examples.

The developed program to demonstrate and test topology based interlocking is presented in section 5.3. Necessary inputs and the proceeding to enable topology based interlocking with the standard IEC 61850 is presented.

5.1 Interlocking Decisions

5.1.1 Using Length of Parallel Path

Safety relevant interlocking can be clearly solved by checking the potential double or by identifying a parallel path. This part is solved in theses [10], [11] and [29]. But it can be shown that for operational interlocking this information is insufficient for some configurations. The previously mentioned theses propose to use pattern recognition for operational interlocking. Therefore it is necessary to detect the patterns and define the patterns to generate enable or interlock signals. To detect patterns the authors propose to use the search strategy to return found switch elements as a list. These lists need then to be checked with defined patterns or criteria, which is a rather complex and inefficient procedure because complex return values with all passed switches are needed. These return values are then checked with previously defined criteria. The patterns are formulated in [10] switch by switch which requires adaptations for each configuration due to different substation configurations. Patterns proposed in [27] and [29] are defined for different switch configurations by counting and combining the number of special switch types. But these criteria are not suitable for configurations with more than two busbars.

The new solution presented in this theses to increase performance and flexibility uses the new properties for nodes and switches introduced in section 4.2. The new node potentials are needed for operational interlocking decisions, if no parallel path exists. The new introduced length of switches allows to reduce the pattern recognition to one value only - **the length of the parallel path**. As it is shown in the following section, the length provides a sufficient and simple criterion for most operational interlocking. For some decisions additional criteria to the length of the parallel paths need to be checked. Due to the adaptation of length of switches, modifications are necessary for BFS, so that the length of the shortest parallel path can still be evaluated. The length of the shortest parallel path delivers for some switches already a sufficient criterion to generate enable or interlock signals. In other cases all relevant parallel paths have to be identified with the modified DFS, using the modifications of the search strategies that are described in section 4.4. The next sections present for different substation configurations and switch types the detectable potential doubles and length of parallel paths and discuss enable and interlock criteria.

5.1.2 Safety Relevant Interlocking

Safety relevant interlocking based on the topology is presented in theses [10, p. 20] and [11, p. 8]. As mentioned in section 2.2, rules for safety relevant interlocking can be derived from standards for circuit breakers, disconnectors and earthing switches. The rules presented in section 2.2 are extended for the new potentials defined in section 4.2.1.

Circuit Breakers

Circuit breakers are able to break and make current. The safety relevant limitation for any circuit breaker is that it must not connect live nodes with grounded nodes. This means for the operation of a circuit breaker that:

(a) The operation of a circuit breaker is allowed if a parallel path for the circuit breaker exists, which indicates that both switch contacts are already connected.

(b) The operation of a circuit breaker is also allowed when one of the following potential doubles is detected: S-L, S-BB, S-T, S-I, L-L, L-BB, L-T, L-I, BB-T, BB-I, T-I, or I-I. If the not grounded node provides the isolation distance[11] then the potential doubles E-L, E-BB, E-T or E-I are allowed.

(c) The operation of a circuit breaker for the potential double S-S is only allowed if the voltages are synchronised.

(d) A circuit breaker must not be operated when the potential double E-S is detected.

Disconnector

Disconnectors must not make or break current. Therefore, the allowed potential doubles are further restricted compared to the ones which are allowed for the circuit breaker. This means for the operation of a disconnector that:

(a) The operation of a disconnector is allowed if a parallel path for the disconnector exists, which means that both contacts of the switch are already connected.

[11] The isolation distance is given when all adjacent disconnectors are in the open position. Positions of a circuit breaker are not relevant because this switch does not provide an isolation distance. If a circuit breaker is connected to the node, it is necessary to check both connection points of the circuit breaker for the isolation distance.

(b) The operation of a disconnector is allowed if one of the following potential doubles is detected: S-BB, S-T, S-I, L-L, L-BB, L-T, L-I, BB-T, BB-I, T-I or I-I. The potential doubles: E-L, E-BB, E-T or E-I allow to operate the disconnector if the not grounded node provides the isolation distance [11].

(c) A disconnector must not be operated when one of the following potential doubles is detected: E-S, S-S or S-L.

Earthing Switches

Earthing switches are needed for earthing equipment in substations to provide safe conditions for maintenance. One side of an earthing switch is always connected to ground. Earthing switches have in general no parallel path because only one earthing switch is needed for grounding a single node in a switchgear. Therefore, following conditions are needed for earthing switches:

(a) The operation of earthing switches is allowed if one of the following potential doubles is detected: E-E, E-L, E-BB, E-T or E-I. For potential doubles: E-L, E-BB, E-T or E-I the operation of earthing switches is only allowed if the isolation distance of the node to be switched is given. This means that all adjacent disconnectors must be in the open position. Positions of a circuit breaker are not relevant because this switch does not provide an isolation distance. But if a circuit breaker is connected to the earthing switch, it is necessary to check whether both connection points of the circuit breaker provide the isolation distance. It is proposed in this thesis to do this with BFS.

(b) Earthing switches must not operate if the potential double E-S is detected. [12]

(c) Earthing switches must not operate if the isolation distance is not given for potential doubles: E-L, E-BB, E-T or E-I.

[12] To ground a source node additional information which is provided in the topology is needed, to ensure that the source is not live and the node is isolated.

5.1.3 Operational Interlocking

Some solutions for operational interlocking are introduced in the presented literature. But these solutions do not cover substation configurations with more than two main busbars. Therefore following new solutions are presented in this thesis:

- The proposed rules are formulated that they are suitable for any number of main busbars.
- New is that unnecessary operation of the circuit breakers can be avoided with the new introduced node potential "BB".
- Grouping of feeders is possible with the new introduced node property "Network Group" to avoid connections of selected feeders.
- New to topology based interlocking conditions are operational conditions for cross-tie switches, shunt disconnectors and the 1 ½-breaker method.
- New is that operational interlocking conditions for ring busbars can be applied for any number of feeders[13].

New to all following topology based interlocking rules is that the switch types are detected automatically and the length of parallel path is used as criterion for operational interlocking decisions.

This section presents operational interlocking conditions that do not depend on the type of substation. Operational decisions are checked only if operation is allowed after checking safety relevant conditions. Operational interlocking conditions that depend on the topology are discussed in sections 5.1.4 to 5.1.8.

Keep Switching Sequence

Every switch operation increases the wear of switches and this reduces lifespan. To prevent unnecessary switch operations it is useful to restrict the closing of circuit breakers. The sequence for the operation of switches is: close first disconnectors and afterwards close the circuit breaker to switch the current. It is possible to realise "keep the switching sequence" by checking the potential double for circuit breakers. Therefore, the potential

[13] In [29] topology based operational interlocking for ring busbars with exactly four feeders was introduced.

doubles for closing any circuit breaker requires potential doubles with potentials higher than I. This results in following rules:

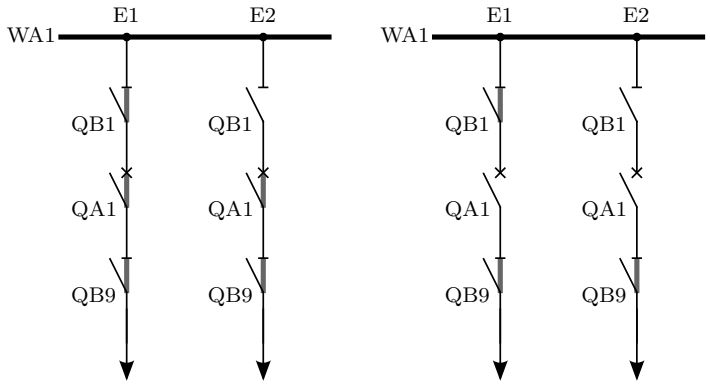
(a) Closing a circuit breaker is allowed if potential double: S-L, S-BB, S-T, L-BB, L-T or BB-T or E-L, E-BB, E-T is detected.

(b) Therefore a circuit breaker must not be closed when potential double: S-I, L-I, T-I or I-I or E-I is detected.

(c) Opening a circuit breaker does not require further restrictions compared to the safety relevant doubles.

Figure 5.1 gives two example switch configurations of a single busbar with two feeders to discuss the switching sequence. The examples are discussed for circuit breakers in feeders but the switching sequence is valid for circuit breakers in coupling bays and for transformers as well. Figure 5.1(a) gives an example why keeping the switching sequence is needed to avoid unnecessary switch operation. In feeder E1 disconnectors E1-QB1, E1-QB9 and circuit breaker E1-QA1 are closed and so this feeder is connected to the busbar. Circuit breaker E2-QA1 and disconnector E2-QB9 are closed and disconnector E2-QB1 is open in feeder E2. If feeder E2 should be connected to the busbar and so to the other feeder, it is necessary to first open circuit breaker E2-QA1 and then close disconnector E2-QB1 and after that close circuit breaker E2-QA1 again. The configuration in feeder E2 is avoided when the switching sequence is always taken into account. But if the situation occurs as in figure 5.1(a) it is needed to allow to open circuit breaker E2-QA1 to return to a safe operation without deactivating the switching sequence. Therefore closing a circuit breaker is restricted and opening not (rule c).

In figure 5.1(b) feeder E1 switch E1-QB1 and E1-QB9 are closed and switch E1-QA1 is open. In feeder E2 switch E2-QB9 is closed and switch E2-QB1 and E2-QA1 are open. Busbar WA1 has the potential BB and it is therefore possible to check the switching sequence. Switch E1-QA1 has the potential double S-BB and is allowed to be closed (rule a). But switch E2-QA1 has the potential double S-I and is not allowed to be closed (rule b). If busbar WA1 would have the potential I instead of the BB, newly proposed in this thesis, it would not be possible to differentiate both situations. Both switches E1-QA1 and E2-QA1 would have the same potential double S-I and therefore the switching sequence could not be guaranteed.



(a) Example 1 (b) Example 2

Figure 5.1: Single busbars examples to discuss switching sequence

To Guarantee Continuous Power Supply

The check if continuous power supply is given, effects circuit breakers because disconnectors are not allowed to break current. Therefore, limits for opening circuit breakers are needed. An interlock signal due to this condition might be overruled in case of an emergency to enable load shedding. In general continuous power supply requires that loads must not be disconnected from sources under normal operation conditions. This means that:

(a) Opening a circuit breaker is allowed, if a parallel path exists (e.g. with a bypass switch or a shunt disconnector).

(b) Opening a circuit breaker is allowed if the potential double: S-S is detected. In this case opening the circuit breaker separates two areas in which sources are available to supply connected loads.

(c) Opening a circuit breaker for detected potential doubles: L-L, L-BB, L-T, L-I, BB-T, BB-I, T-I or I-I is allowed as well. Because loads are not connected to a source and opening would not cause any interruption in supply.

(d) Circuit breakers must not be opened if continuous power supply is needed, if potential double: S-L is detected. This includes that the source is not allowed to be disconnected from loads because it is the only source, and to disconnect a single load that is connected to one or more sources as well.

Do Not Forward Earth Potential

In general earthing switches are installed in a substation where they are needed for grounding. Therefore forwarding earth potential is not needed and not wanted to keep clear conditions in the substations. This means that disconnectors and circuit breakers are not allowed to be closed if the disconnector is connected to ground. That means for circuit breakers and disconnectors that:

(a) Circuit breaker and disconnector must not be closed if potential double: E-L, E-BB, E-T or E-I is detected.

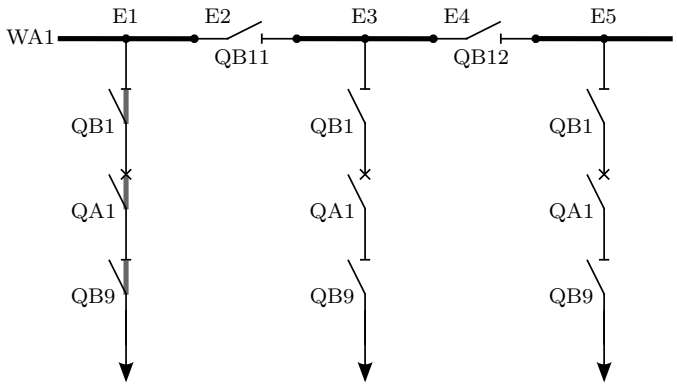
Keep Capacitive Currents Small

Each busbar section has capacity. Connecting a busbar section to a source causes a capacitive charging current. Two isolated busbars sections have a higher capacity, which leads of course to a higher charging current. Therefore sections are supposed to be connected to a live busbar one by one. This means for sectionalizers that:

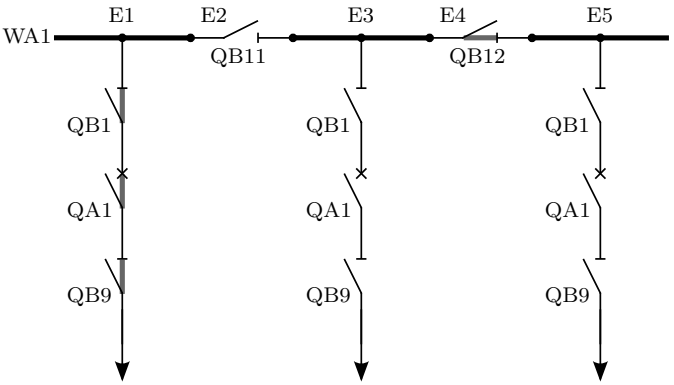
(a) Sectionalizers (DIS-C-S) must not be closed when potential double S-BB is detected, and the side of the sectionalizer with potential BB is connected to more than one busbar section. It is proposed to use BFS to check if the busbar section is not connected to any other busbar sections.

Figure 5.2 shows two examples of three single busbar sections.
indent Example 1: Sectionalizer E2-QB11 in figure 5.2(a) is allowed to be closed because the right busbar section is isolated.

Example 2: Figure 5.2(b) shows a configuration in which the sectionalizer E2-QB11 is not allowed to be closed. The reason is, that sectionalizer E4-QB12 is closed as well. Connecting two sections at once causes higher charging currents and should be prevented.



(a) Example 1, smaller capacitive charging current for closing switch E2-QB11



(b) Example 2, larger capacitive charging current for closing switch E2-QB11

Figure 5.2: Single busbars examples to discuss capacitive charging currents

Do Not Couple Network Groups

In section 4.2.2 network groups are introduced for nodes. Due to operational reasons feeders are grouped. This can be done to:

- Limit the short circuit power by limiting the number of sources connected
- Limit the source current by limiting the number of loads connected to one or more sources
- Obtain clarity in the grid
- Prevent coupling of asynchronous parts

Therefore it is necessary to evaluate the network group with BFS as it is proposed in section 4.2.2. In case of an emergency avoiding the coupling of network groups can be deactivated for following conditions[14]:

- The feature network groups to prevent coupling of asynchronous parts is not used.
- The short circuit power is in a range that the circuit breakers are able to handle. For example if some sources are switched off for maintenance.
- The loads do not exceed the maximum power of the sources. For example if some loads can be supplied with power from another station.

5.1.4 Operational Interlocking Conditions for Normal Busbars

Disconnector in Coupling Bay Connected to a Busbar

Disconnectors in a coupling bay connected to a busbar (DIS-C-BB) are used to couple busbars with the circuit breaker. Therefore two disconnectors in double or multiple busbar configurations must not connect the busbars without a circuit breaker. This leads to following restrictions:

(a) DIS-C-BB is allowed to be closed if potential double: S-I, L-I, BB-I, or E-I is detected.

(b) DIS-C-BB must not be closed if any parallel path exists.

[14] These conditions are currently not checked with the topology based information and need input from the operator.

(c) If DIS-C-BB is connected to an auxiliary busbar the rules defined in section "Use Auxiliary Busbar as Transfer Busbar" (page 90) need to be taken into account.

(d) A DIS-C-BB must not be opened when a parallel path exists. Opening a parallel path in a coupling bay is done with circuit breaker (CBR-C) or sectionalizers for busbars (DIS-C-S) and is not allowed for DIS-C-BB.

Figure 5.3 shows a double busbar configuration with two coupling bays only.

Example 1: In figure 5.3(a) switch E2-QB1 is closed. E2-QB2 is not allowed to close because the detected potential double BB-BB does not allow that (rule a).

Example 2: In figure 5.3(b) again switch E2-QB1 is closed. Additionally, switches E1-QB1, E1-QA1 and E1-QB2 in coupling bay E1 are closed, so that a parallel path exists for switch E2-QB2 and closing this switch is not allowed (rule b).

Example 3: Not closing a parallel path with a DIS-C-BB does not allow E2-QB2 in figure 5.3(c) to close. The parallel path with closed switches E2-QB21, E1-QB21, E1-QA1 would be allowed but is forbidden by rule b. This is necessary to prevent illegal closing of parallel paths like the one presented in figure 5.3(b). Closing parallel path in a coupling bay is possible with coupling circuit breaker (CBR-C). In this situation it would be necessary to open the coupling circuit breaker E2-QA1 and close afterwards the disconnector E2-QB2 and then close the coupling circuit breaker E2-QA1 again, because this is a valid parallel path for the coupling circuit breaker.

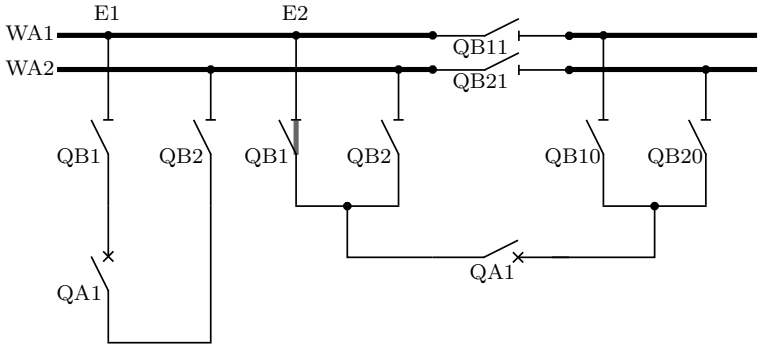
Disconnector in Feeder or Transformer Bay Connected to a Busbar

Disconnectors in a feeder or transformer bay connected to a busbar (DIS-F-BB or DIS-T-BB) have the same basic interlocking rules. Additional restrictions for DIS-T-BB are discussed in the section "Do Not Energize a Transformer with Disconnector". To prevent coupling of busbars in a feeder without a connection of busbars with coupling switches the potential double and parallel paths have to be checked. This means that:

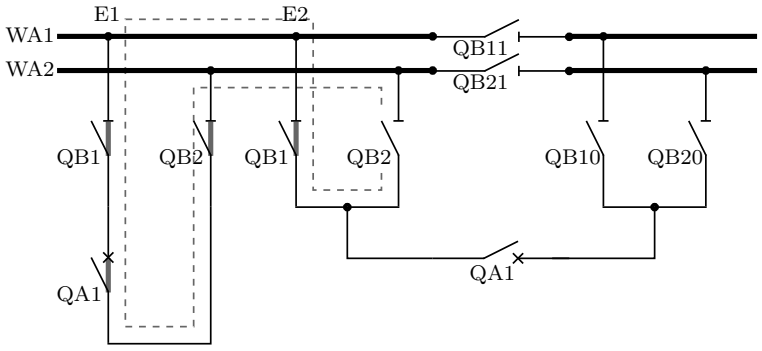
(a) Closing a DIS-F-BB or DIS-T-BB is allowed if the potential double S-I, L-I or BB-I, S-T, L-T, or BB-T[15] is detected and no parallel path exists[16].

[15] Potential doubles for DIS-T-BB might not be allowed due to the rule "Do Not Energize a Transformer with Disconnector" which is checked separately.

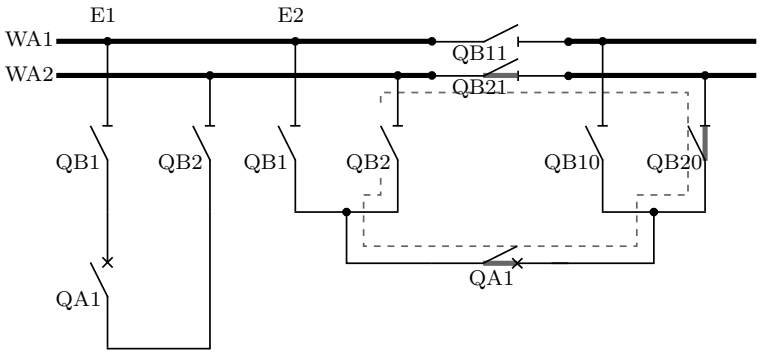
[16] Potential doubles are not derived if a parallel path exists, because both sides of the switch are connected to the same potential. To clarify the criterion, the existence of a parallel path is additionally excluded.



(a) Example 1, Potential double BB-BB does not allow to close E2-QB2



(b) Example 2, Parallel path (dashed line) does not allow to close E2-QB2



(c) Example 3, Parallel path (dashed line) does not allow to close E2-QB2

Figure 5.3: Examples with possible parallel paths for DIS-C-S E2-QB2

(b) Or closing a DIS-F-BB or DIS-T-BB is allowed if the potential double L-BB or S-BB is detected and the feeder or transformer is not connected to the busbar and no parallel path exists.

(c) Or closing a DIS-F-BB or DIS-T-BB is allowed if a parallel path exists with the length of four and the feeder is connected to only one busbar. A parallel path with the length of four indicates that the parallel path passes a coupling bay that connects the busbars. The length of four includes one feeder busbar disconnector (DIS-F-BB) and two coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of a transversal coupling. Example 2 in figure 5.5 presents a path with the length of four. Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

(d) Opening a DIS-F-BB or DIS-T-BB does not require operational restrictions and is therefore allowed if the safety relevant conditions are fulfilled.

Example 1: Figure 5.4 shows feeder E1 with all switches opened. Closing switch E1-QB1 is allowed because the potential double is BB-I (rule a). If other feeders are connected to busbar WA1 then potentials S-I or L-I would be detected and closing would not be allowed. Closing switch E2-QB1 would be allowed as well in this situation. Potential double S-BB or L-BB is allowed and the feeder is not connected to any busbar with switches E2-QB2 or E2-QB3 (rule b).

Example 2: Figure 5.5 shows a configuration with closed switches E3-QB1, E3-QA1 and E3-QB30 in coupling bay E3 and closed switches E1-QB3, E1-QA1 and E1-QB9 in feeder E1. These switches close the parallel path marked with the dashed line for switch E1-QB1. The parallel path has a length of four. Switch E1-QB3 is closed and E1-QB2 is open so that only one other switch is connected to a busbar so that closing E1-QB1 is allowed (rule c). In feeder E2 switch E2-QB1 is not allowed to close because no parallel path exists and switch E2-QB2 is already closed in the bay.

Example 3: Figure 5.6 shows a parallel path (dashed line) for switch E1-QB1 that passes E1-QB3 and in feeder E2 switches E2-QB1 and E2-QB3. This path does not include a connection of the two busbars with a coupling as the path in figure 5.5 does. The length of the path is only three. Closing switch E1-QB1 is unsafe because the detected path does not include coupling bays that would connect the busbars (rule c).

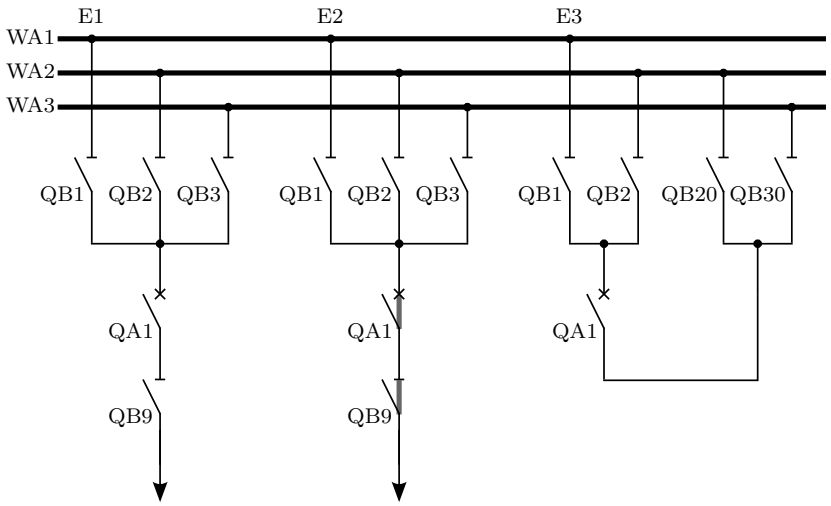


Figure 5.4: Example 1, Potential double to close E1-QB1 and E2-QB1

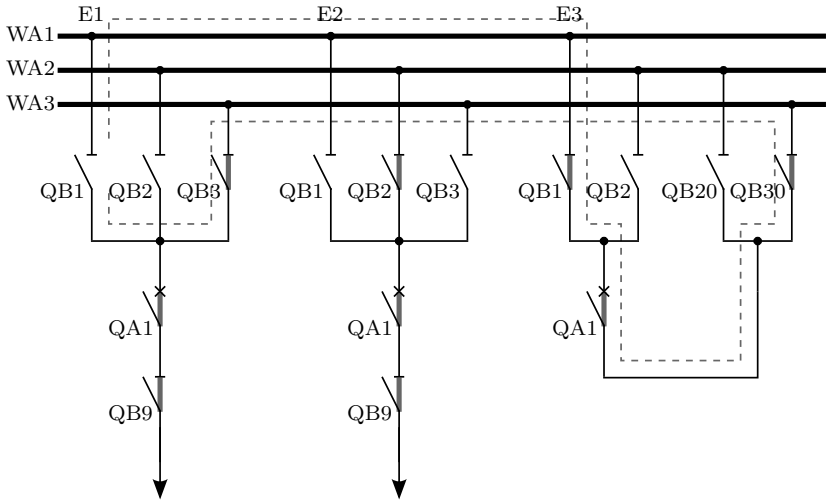


Figure 5.5: Example 2, Parallel path of length 4 (dashed line) and open switch E1-QB2 allows to close switch E1-QB1

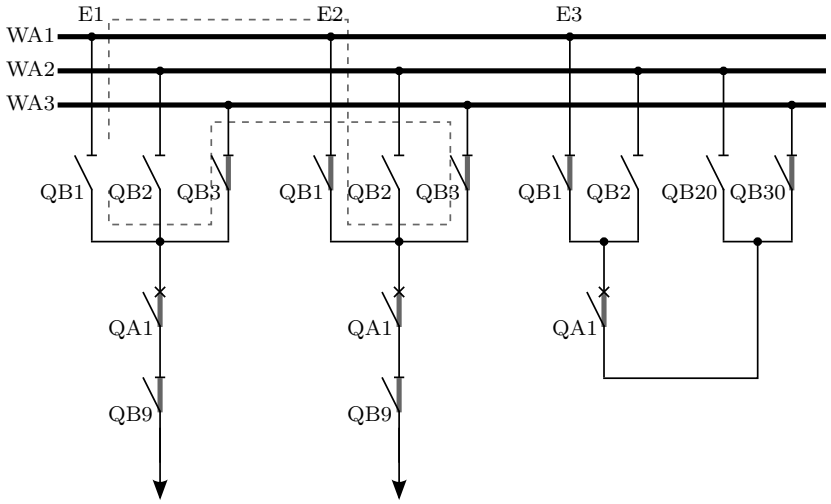


Figure 5.6: Example 3, Parallel path of length 3 (dashed line) that is unsafe to close E1-QB1 because it includes no coupling

Example 4: Figure 5.7 shows a configuration where operational interlocking should not allow to close E1-QB1. The parallel path marked with a dashed line has a length of seven and therefore does not allow to close switch E1-QB1. The length of seven indicates that no direct connection between the busbars exists (rule d).

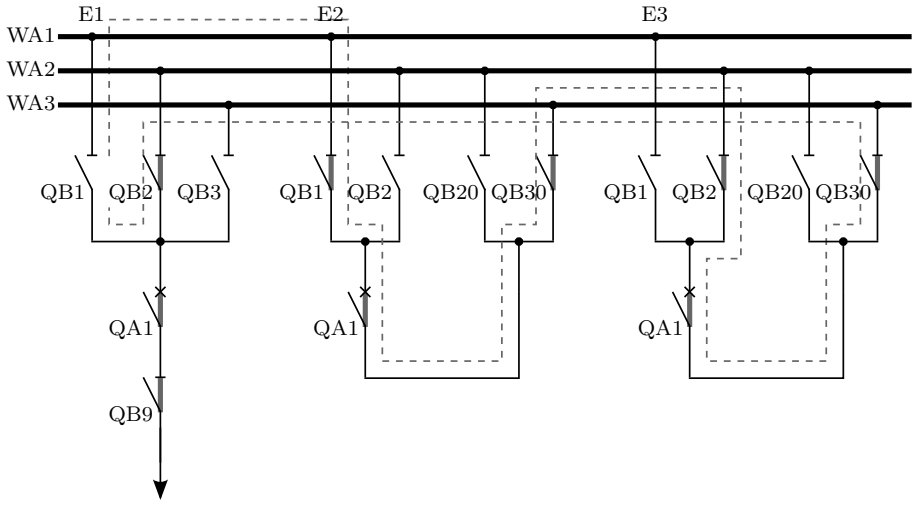


Figure 5.7: Example 4, Parallel path of length 7 (dashed line) does not allow to close E1-QB1

Use Auxiliary Busbar as Auxiliary Busbar

Auxiliary busbars can be used to couple directly two feeders to isolate their circuit breakers for maintenance, when this option is enabled. The feeders are coupled with disconnectors only and protection for lines has to be provided from adjacent substations. Connecting more feeders would not provide selectivity any more, so that the number of allowed feeders connected to an auxiliary busbar is restricted to two. This means that:

(a) A bypass switch (DIS-F-Y) is allowed to be closed if no parallel path exists and no other switch is connected to the busbar, which can be checked automatically by the proposed solution using BFS.

(b) Or a bypass switch (DIS-F-Y) is allowed to be closed if exactly one parallel path exists with the length of seven. This guarantees that the path does not pass two main busbars and only one DIS-F-Y is connected to the auxiliary busbar. The length of seven includes one bypass switch (DIS-F-Y) and two busbar disconnectors (DIS-F-BB) two feeder circuit breakers (CBR-F) and two feeder disconnectors (DIS-F). Example 1 in figure 5.8 presents a path with the length of seven. Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

The number of connected feeders can be checked with BFS, by counting adjacent switches to the auxiliary busbar.

Example 1: Figure 5.8 shows a double busbar with auxiliary busbar configuration. Feeder E1 is connected to busbar WA1 and auxiliary busbar WA7, because switches E1-QB1, E1-QA1, E1-QB9 and E1-QB7 are closed. Feeder E2 is connected to busbar WA1 as well. Closed switches are E2-QB1, E2-QA1 and E2-QB9. Closing switch E2-QB7 will be allowed if bypass operation should be initialized because the parallel path (dashed line) has a length of seven and only one feeder is connected to the auxiliary busbar WA7 (rule b).

Example 2: Figure 5.9 shows a similar configuration as in example 1. But feeder E2 is now connected to busbar WA2, as switches E2-QB2, E2-QA1 and E2-QB9 are closed. Switches E3-QB1, E3-QA1 and E3-QB2 are closed in coupling bay E3. Again a parallel path exists for switch E2-QB7 but the length is ten because the path passes coupling and therefore the operation is not allowed (rule b).

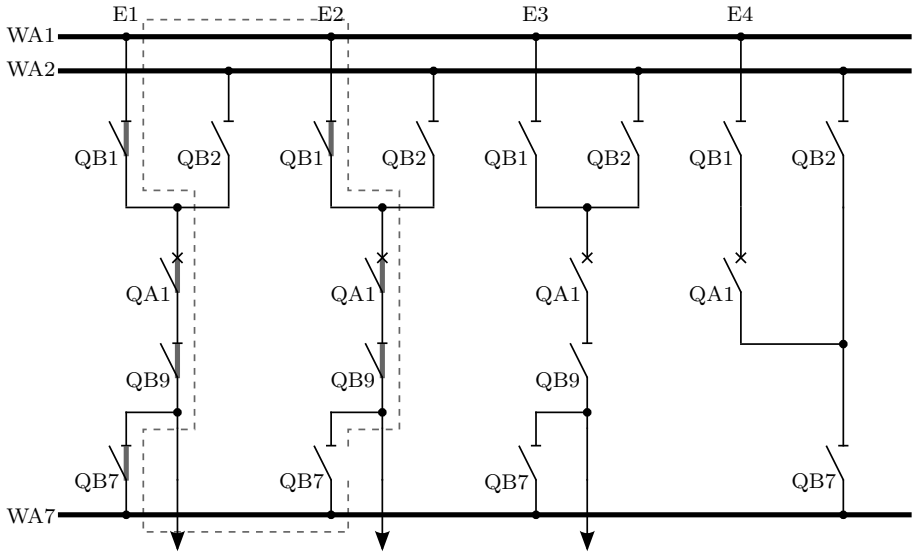


Figure 5.8: Example 1, Parallel path of length 7 (dashed line) allows to close switch E2-QB7

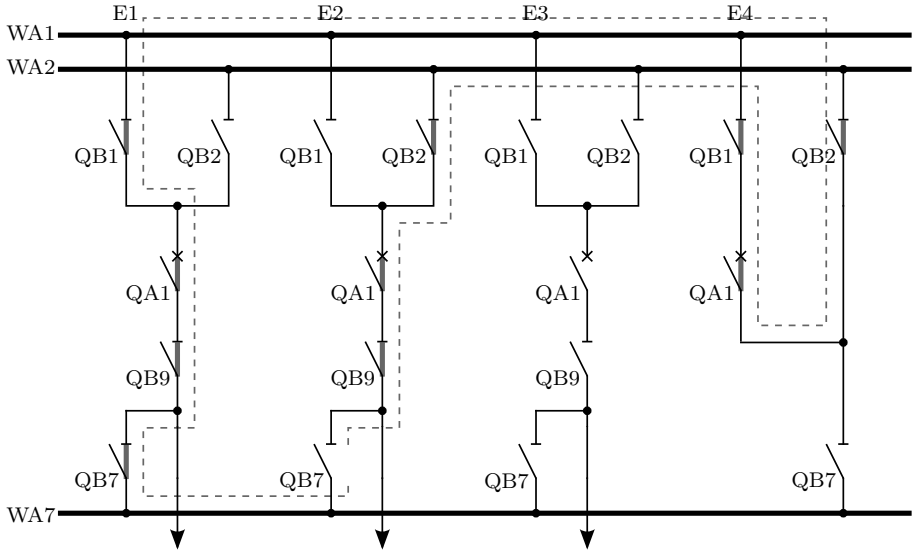


Figure 5.9: Example 2, Parallel path of length 10 (dashed line) does not allow to close switch E2-QB7

Use Auxiliary Busbar as Transfer Busbar

Auxiliary busbars can be used as transfer busbars as well, when this option is enabled. One feeder can be connected with the bypass switch (DIS-F-Y) QB7 to the auxiliary busbar. A coupling bay is then used to connect the feeder to a main busbar in the substation, while allowing maintenance of the circuit breaker in the feeder. Connecting more feeders would not provide selectivity any more, so that only one coupling and one feeder is connected to the auxiliary busbar. There are two options presented in [10, p. 113] for switching a feeder to the auxiliary busbar used as transfer busbar:

- Connecting the feeder first to the auxiliary busbar would risk destroying the disconnector if the busbar is connected with forgotten grounding equipment, but no commutation currents occur.
- Connecting the coupling first to the auxiliary busbar the coupling circuit breaker could handle forgotten grounding equipment that is connected to the auxiliary busbar. But the bypass switch has to switch commutation currents.

This results in the following operational interlocking conditions which can be automatically checked by the method proposed in this thesis:

(a) Closing a bypass switch (DIS-F-Y) is allowed if the allowed potential double for a disconnector is given and
  - No parallel path exists
  - And no other switch is connected to the busbar, which can be checked automatically by the proposed solution using BFS
  - And the feeder has to be connected first to the auxiliary busbar

(b) Or closing a bypass switch (DIS-F-Y) is allowed if
  - if the coupling has to be connected first to the busbar.
  - and a parallel path exists with the length of six, so that it is guaranteed that the path does not pass two main busbars. The length of six includes one feeder disconnector (DIS-F), one feeder circuit breaker (CBR-F), one feeder busbar disconnector (DIS-F-BB), two coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C). Example 1 in figure 5.8 presents a path with the length of six. Even multiple longitudinal coupling

with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

(c) A disconnector of a coupling bay (DIS-C-BB) connected to an auxiliary busbar is allowed to be closed if the potential double BB-I is detected and

- No parallel path exists
- And no other switch is connected to the busbar, which can be checked automatically by the proposed solution using BFS
- And the coupling has to be connected first to the auxiliary busbar

(d) Or a disconnector of a coupling bay (DIS-C-BB) connected to an auxiliary busbar is allowed to be closed

- if the feeder has to be connected first to the busbar
- and only one switch is connected to the auxiliary busbar, which can be checked automatically by the proposed solution using BFS.

(e) Closing the coupling circuit breaker CBR-C is allowed if

- The coupling is connected to the auxiliary busbar
- and exactly one parallel path with the length of six is detected, so that it is guaranteed that the path does not pass two main busbars
- and that the feeder has to be connected first to the busbar.

The length of six includes one feeder disconnector (DIS-F), one feeder circuit breaker (CBR-F), one feeder busbar disconnector (DIS-F-BB), one bypass switch (DIS-F-Y), and two coupling busbar disconnectors (DIS-C-BB) of a transversal coupling. Example 2 in figure 5.11 presents a path with the length of six. Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

Example 1: Figure 5.10 shows a double busbar with auxiliary busbar configuration. Feeder E1 is connected to busbar WA1. Switches E1-QB1, E1-QA1 and E1-QB9 are closed. Coupling bay E3 connects busbar WA1 with busbar WA7 with switches E3-QB1, E3-QA1 and E3-QB7. Then closing switch E1-QB7 is allowed because the parallel path has a length of six (rule b).

Example 2: Figure 5.11 shows a double busbar with auxiliary busbar configuration.

Feeder E1 is connected to busbars WA1 and WA7. Switches E1-QB1, E1-QA1, E1-QB9 and E1-QB7 are closed. In coupling bay E3 switches E3-QB1 and E3-QB7 are closed. Then closing switch E3-QA1 is allowed because the parallel path has a length of six (rule b).

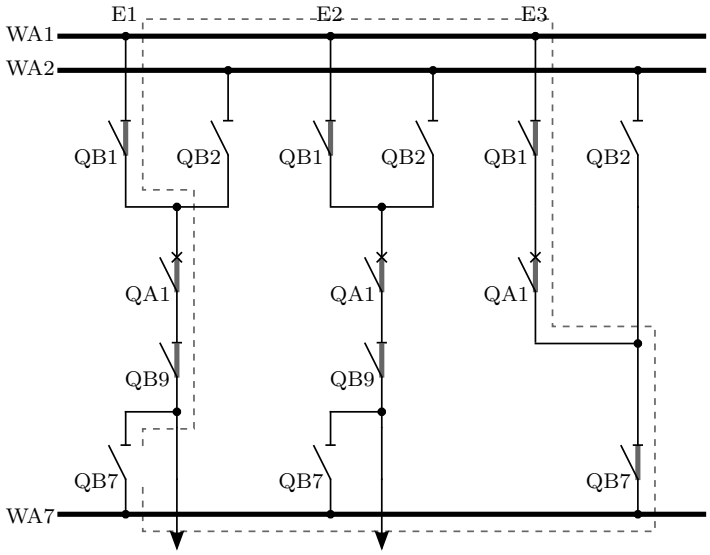


Figure 5.10: Parallel path of length 6 (dashed line) allows to close switch E1-QB7

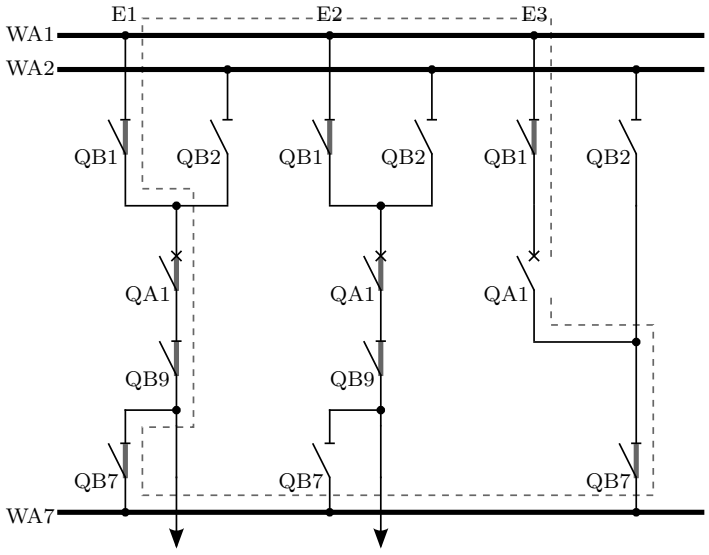


Figure 5.11: Parallel path of length 6 (dashed line) allows to close switch E3-QA1

Combined Busbar as Auxiliary or Transfer Busbar

Combined busbars can be used as main busbars in normal operation or as auxiliary or transfer busbar during maintenance. To change the mode of operation from main to auxiliary or transfer busbar the number of connected switches has to be checked:

1. Use combined busbar as auxiliary busbar is allowed when exactly two feeders are connected to the combined busbar.

2. Use combined busbar as transfer busbar is allowed when exactly one feeder and one coupling is connected to the combined busbar.

Both criteria can be checked with BFS. Using the combined busbar as auxiliary busbar allows to directly connect two feeders with bypass disconnectors (DIS-F-Y). Restrictions are therefore necessary as follows:

(a) Closing DIS-F-Y is allowed if a parallel path with length of three is detected. The length of three includes one feeder disconnector (DIS-F), one feeder circuit breaker (CBR-F) and one feeder busbar disconnector (DIS-F-BB). Example 1 in figure 5.12 presents a path with the length of three. Longitudinal coupling will not be part of such a path because in this case the parallel path will always be closed in the feeder.

(b) Closing a DIS-F-BB to connect to the auxiliary busbar is only allowed if in the same feeder the bypass switch DIS-F-Y is closed.

(c) A DIS-C-BB must not be connected to the auxiliary busbar, which can be checked with BFS.

(d) CBR-F is allowed to be closed if a parallel path exists with the length of three or the potential double is allowed. The length of three includes one feeder disconnector (DIS-F), one bypass disconnector (DIS-F-Y) and one feeder busbar disconnector (DIS-F-BB). Example 3 in figure 5.14 presents a path with the length of three. Longitudinal coupling will not be part of such a path because in this case the parallel path will always be closed in the feeder.

Example 1: Figure 5.12 shows a configuration that allows to use the combined busbar as auxiliary busbar. Feeder E1 and feeder E2 are connected with switches E1-QB2 and

E2-QB2 to busbar WA2/WA7. Feeder E3 and coupling bay E4 are not connected. Parallel paths with the length of three are marked with dashed lines that allows to close switches E1-QB7 and E2-QB7 (rule a).

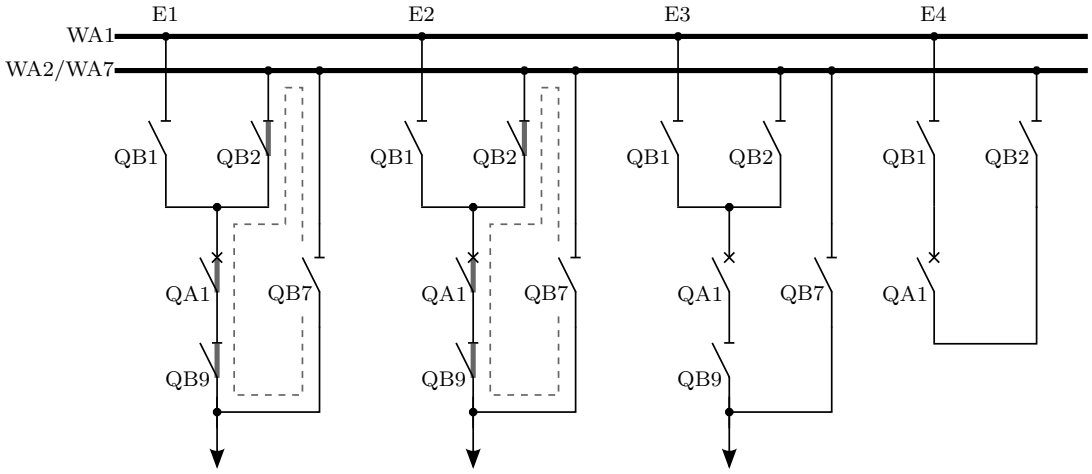


Figure 5.12: Parallel paths of length 3 (dashed lines) allow to close switches E1-QB7 and E2-QB7

Example 2: Figure 5.13 shows a configuration which does not allow the use of the combined busbar as an auxiliary busbar. Only feeder E1 and the coupling E4 are connected to the auxiliary busbar. Switch E2-QB7 has a parallel path (dashed line) but the length is equal to six so that operational interlocking made possible with methods in this thesis. This is because switches E1-QB1, E1-QA1, E1-QB9 and E1-QB7 would couple the busbars which is not allowed (rule a).

Example 3: Figure 5.14 shows a configuration that allows to close circuit breaker E1-QA1. The parallel path is marked with a dashed line. The path with closed switches E1-QB2, E1-QB7 and E1-QB9 in bay E1 does not include a busbar coupling and therefore allows to close switch E1-QA1 to return to normal operation (rule d).

Using the combined busbar as transfer busbar allows to connect a feeder with a bypass and a coupling to a main busbar. Restrictions are therefore necessary as follows:

(a) Closing DIS-F-Y is allowed if a parallel path with length of three is given. The length of three includes one feeder disconnector (DIS-F), one feeder circuit breaker (CBR-F) and one feeder busbar disconnector (DIS-F-BB). Example 1 in figure 5.15 presents a path with the length of three. Longitudinal coupling will not be

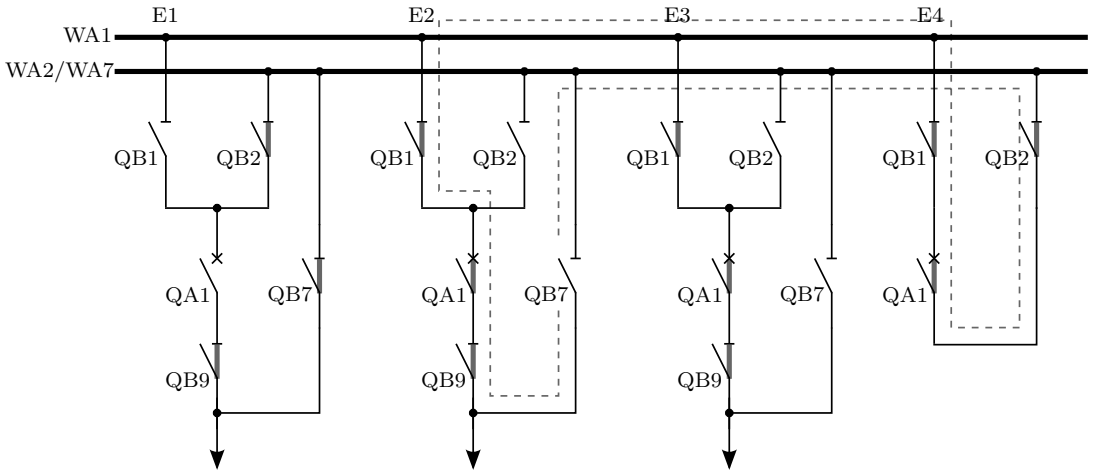


Figure 5.13: Parallel path of length six (dashed line) does not allow to close switch E2-QB7

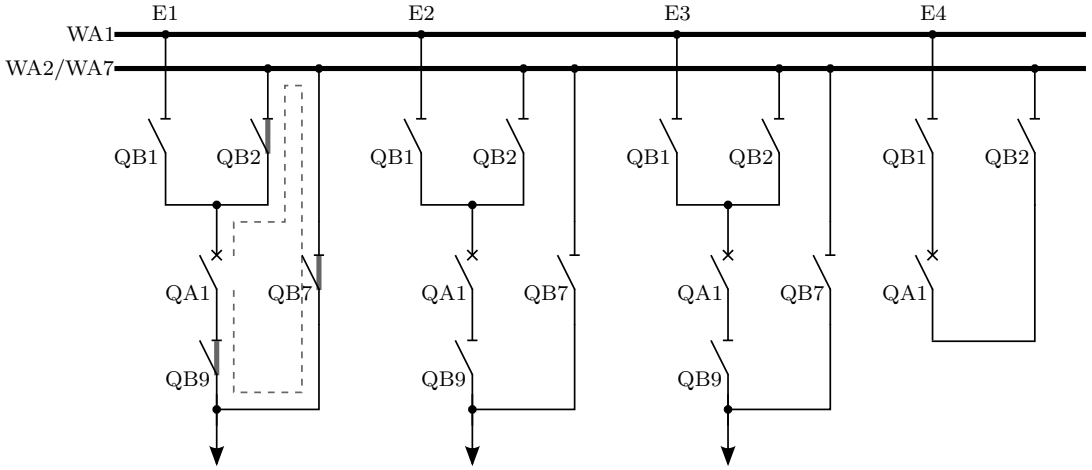


Figure 5.14: Parallel path of length three (dashed line) allows to close switch E1-QA1

part of such a path because in this case the parallel path will always be closed in the feeder.

(b) If DIS-F-BB is connected to the auxiliary busbar then closing DIS-F-BB is allowed if the shunt disconnector in the same bay is connected to the busbar as well.

(c) CBR-F is allowed to be closed if a parallel path exists with the length of three or the potential double is allowed. The length of three includes one feeder disconnector (DIS-F), one bypass disconnector (DIS-F-Y) and one feeder busbar disconnector (DIS-F-BB). To return to normal operation closing the feeder circuit breaker the same restrictions are valid as described for the use of a combined busbar as transfer busbar. Both conditions can be automatically detected with the proposed method in chapter 4.

Example 1: Figure 5.15 shows a configuration that allows to use the combined busbar as transfer busbar and the parallel path of length three (dashed line) allows to close switch E1-QB7. Feeder E1 is connected to the combined busbar WA2/WA7 with switches E1-QB2, E1-QA1 and E1-QB9. Coupling bay E4 connects feeders E2 and E3 with feeder E1. This configuration allows to use the combined busbar as transfer busbar. Switch E1-QB7 can be closed because the parallel path with the with length of three allows the operation with the proposed method (rule a).

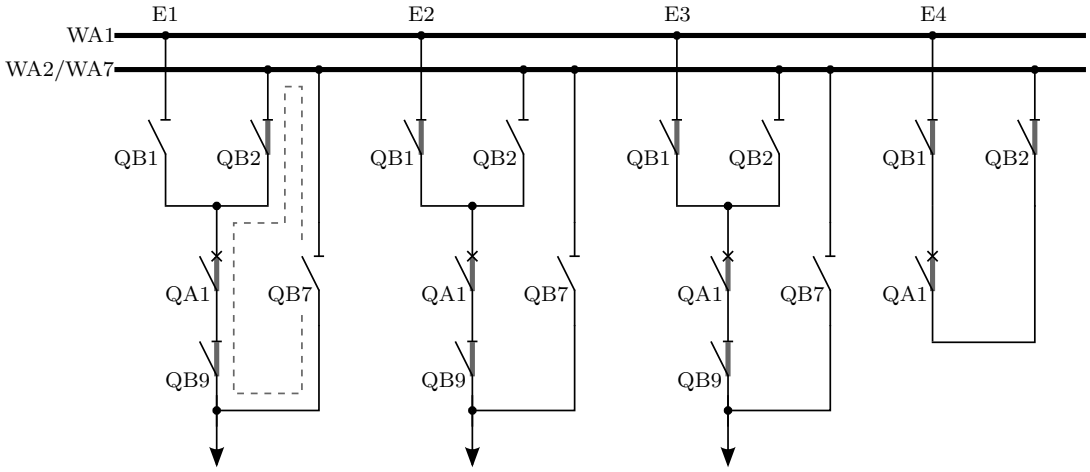


Figure 5.15: Parallel path of length 3 (dashed line) allows to close switch E1-QB7

Example 2: Figure 5.16 shows a configuration that does not allow to close circuit breaker E1-QA1. The parallel path is marked with a dashed line. Bypass switch E1-QB7 would connect with switch E1-QB9, E1-QA1 and E1-QB1 the combined busbar with the main busbar. Coupling bay E4 is part of the parallel path as well and connects both busbars. But operation of the bypass switch is only allowed for a parallel path with the length of three so that the circuit breaker must not close that path (rule a). Opening E1-QB1 and closing E1-QB2 allows to close E1-QA1 to create a configuration that enables opening E1-QB7 to return to normal operation. Then the length of parallel path would be three.

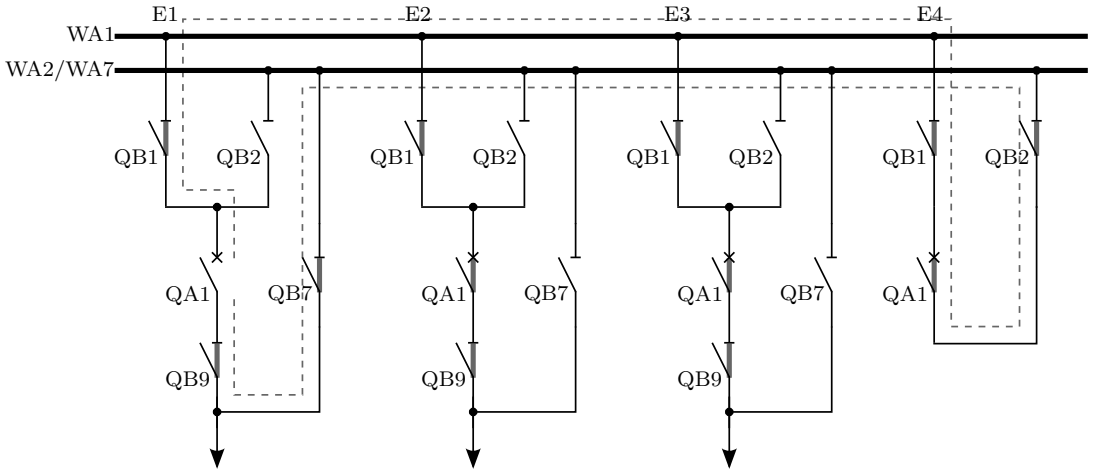


Figure 5.16: Parallel path of length six (dashed line) does not allow to close switch E1-QA1

Circuit Breaker in Feeder Bay

The operation of circuit breakers in feeder bays (CBR-F) is mainly described with safety relevant and general operational rules that depend on the potential double. Parallel paths for CBR-F exist only when shunt disconnectors or bypass switches are used. Depending on the configuration different lengths of the parallel paths are allowed for operation of a circuit breaker:

(a) Closing a parallel path for CBR-F with a length of three is allowed if using a shunt disconnector or a combined busbar, used as auxiliary or transfer busbar. The length of three includes one feeder disconnector (DIS-F), one bypass disconnector

(DIS-F-Y) and one feeder busbar disconnector (DIS-F-BB) in the same bay. Longitudinal coupling will not be part of such a path because in this case the parallel path will always be closed in the feeder.

(b) Closing a parallel path for CBR-F with a length of seven is allowed if the auxiliary busbar is used as auxiliary busbar. The length of seven includes two bypass switches (DIS-F-Y) and two busbar disconnectors (DIS-F-BB), one feeder circuit breakers (CBR-F) and two feeder disconnectors (DIS-F). Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path.

(c) Closing a parallel path for CBR-F with a length of six is allowed if the auxiliary busbar is used as transfer busbar. The length of six includes one feeder disconnector (DIS-F), one bypass switch (DIS-F-Y), one feeder busbar disconnector (DIS-F-BB) and of a transversal coupling, two coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C). Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

The use of the special busbars and switches has to be activated so that this information can be known to the procedure proposed in this thesis to select the right length of the parallel path for interlocking decisions.

Circuit Breaker in Coupling Bay

Coupling switches are needed to couple busbars or provide parallel paths for operational flexibility. Due to the function of a coupling, closing and opening the circuit breaker in a coupling CBR-C is allowed if no parallel path exists. Closing a circuit breaker when a parallel path exist is only needed if a situation is given that explicitly needs a parallel path. This is for example the case if two busbars are connected with feeders only. Then closing the coupling enables to open a switch in the feeders so that the feeders do not couple busbars any longer. But an additional parallel path to another coupling has to be prevented to keep selectivity. This means that:

(a) If parallel paths with a length of four exist and no longer paths are detected, closing a CBR-C is allowed so that the coupling switch provides a parallel path for feeders that couple busbars. The length of four includes two feeder disconnector

(DIS-F-BB), and two coupling busbar disconnector (DIS-C-BB). Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path

(b) CBR-C must not be closed if a parallel path with a length of five or longer is detected. In this case closing the switch would close parallel paths to a coupling circuit breaker and this is not allowed to keep selectivity. The length of five includes four coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of a transversal coupling. Example 1 in figure 5.17 presents a path (dashed line) with the length of five. Even multiple longitudinal coupling with length zero would not increase the length of the path but are not presented in the figure. Parallel paths that are longer then five are presented in figure 5.19.

(c) On the other hand if only one parallel path exists, which has a length of six (four if the topology is reduced) CBR-C is allowed to close if

- the coupling is connected to an auxiliary busbar.
- and the feeder has to be connected first to the auxiliary busbar used as transfer busbar.

The length of six includes one feeder disconnector (DIS-F), one feeder circuit breaker (CBR-F), one feeder busbar disconnector (DIS-F-BB), one bypass switch (DIS-F-Y), and two coupling busbar disconnectors (DIS-C-BB) of a transversal coupling. Figure 5.11 presents a path with the length of six. Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

(d) CBR-C must not be opened if at least one parallel path with the length of four exists. The length of four includes two feeder disconnector (DIS-F-BB), and two coupling busbar disconnector (DIS-C-BB). Example 2 in figure 5.18 presents a path with the length of four. Even multiple longitudinal coupling with length zero would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

(e) CBR-C is allowed to be opened if a parallel path with the length of five exists, because then another parallel coupling is closed. The length of five includes four coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C)

of a transversal coupling. Even multiple longitudinal coupling with length zero would not increase the length of the path.

(f) Is a circuit breaker part of a longitudinal coupling and has therefore the length of zero, then the same restrictions as described for sectionalizers have to be used. The restrictions are presented in the following section "Sectionalizer of Busbars" (page 102).

Example 1: Figure 5.17 shows a double busbar with one feeder E1 and two coupling bays E2 and E3. Feeder E1 is connected with switches E1-QB9, E1-QA1, E1-QB1 and E1-QB2 to both busbars. Coupling E2 connects with switches E2-QB1, E2-QA1 and E2-QB2 both busbars. For switch E3-QA1 two parallel paths can be detected with the modified search methods proposed in this thesis. One path marked with the dash dotted line has a length of four and the other path with the dashed line has a length of five. The parallel path with length five does not allow to close the the switch E3-QA1 (rule b).

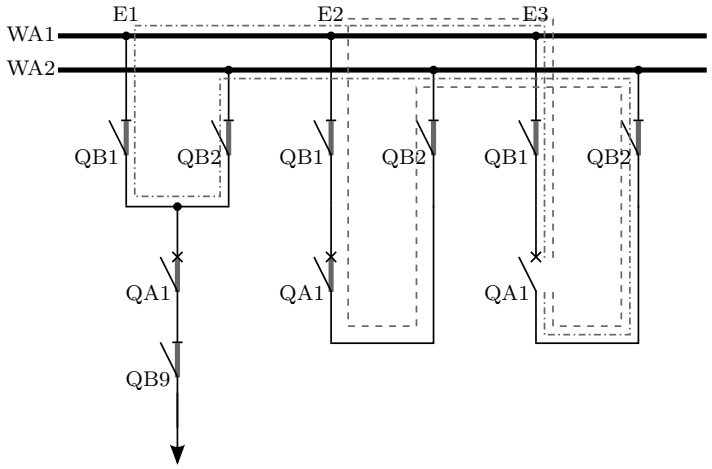


Figure 5.17: Example 1, Parallel path of length five (dashed line) does not allow to close E3-QA1

Example 2: In figure 5.18 coupling E2 is not connected. Feeder E1 is again connected with switches E1-QB9, E1-QA1, E1-QB1 and E1-QB2 to both busbars. Coupling E3 is closed with switches E3-QB1, E3-QA1 and E3-QB2. A parallel path with the length of four for switch E3-QA1 indicates that the busbars are still connected by a feeder. Therefore opening E3-QA1 is not allowed (rule d).

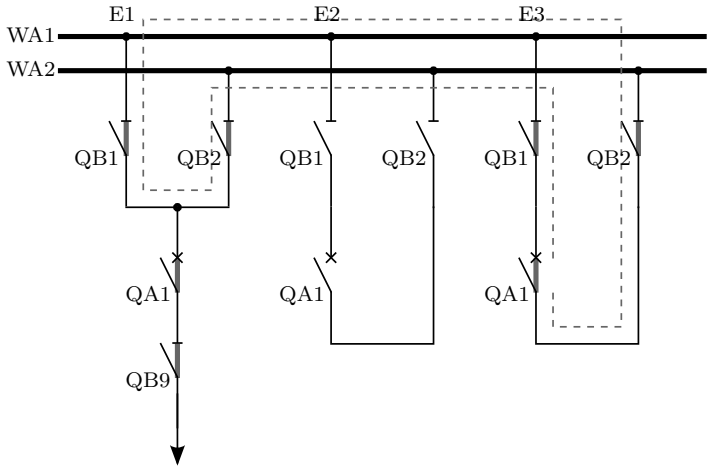


Figure 5.18: Example 2, Parallel path of length 4 (dashed line) does not allow to open E3-QA1

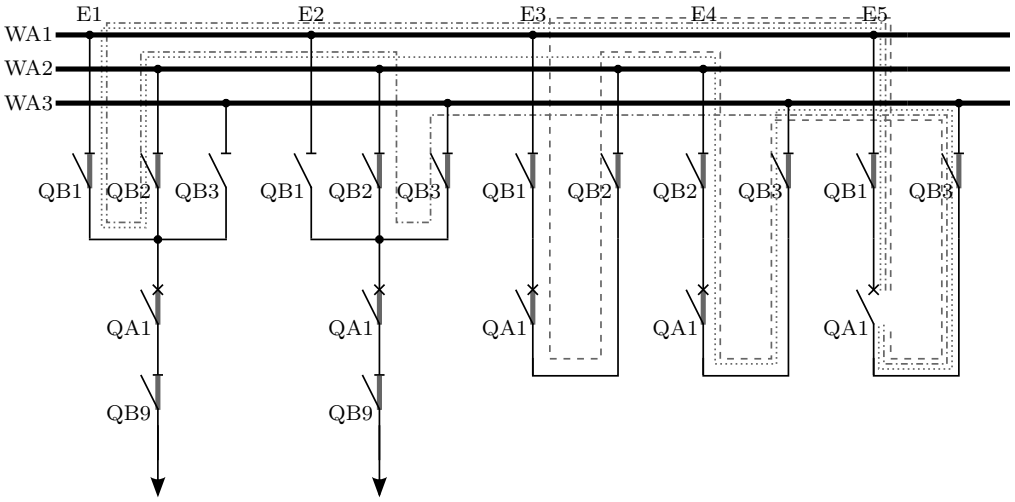


Figure 5.19: Example 3, Parallel paths of length 6 (dash dotted line), of length 7 (dotted line) and of length 8 (dashed line) do not allow to close E5-QA1

Example 3: In figure 5.19 a triple busbar configuration is presented. Feeder E1 is connected to busbars WA1 and WA2. Switches E1-QB1, E1-QB2, E1-QA1 and E1-QB9 are closed. Feeder E2 is connected to busbars WA2 and WA3. Switches E2-QB2, E2-QB3, E2-QA1 and E2-QB9 are closed. Coupling E3 couples busbars WA1 and WA2 for feeder E1. Coupling E4 couples busbars WA2 and WA3 for feeder E2. Switch E5-QA1 has parallel paths with lengths of six (dash dotted line), seven (dotted line) and eight (dashed line) and must therefore not be closed. To ensure selectivity switch E5-QA1 must not be closed (rule b).

Sectionalizer of Busbars

Sectionalizers for busbars (DIS-C-S) are used to directly connect two busbar sections. To keep the capacitive charging currents small restrictions for closing this type of switch are discussed in section 5.1.3. It must be made sure that opening this type of switch does not open a connection that would leave other busbars coupled in a way they are not supposed to be coupled. Therefore, the length of the parallel paths has to be checked:

(a) DIS-C-S is allowed to be opened or closed, if a parallel path has a length of zero. The parallel path includes only switches with the length of zero. This can be one sectionalizers for busbars (DIS-C-S) or two coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of a longitudinal coupling. Example 1 in figure 5.20 presents a path with the length of zero.

Figures 5.20, 5.21 and 5.22 show three examples of parallel paths that enable or interlock the operation.

Example 1: In figure 5.20 sectionalizer E2-QB11 is closed, and switches E2-QB1, E2-QA1 and E1-QB10 are closed. The parallel path is marked with dashed lines. The length of this path is zero because of the new method to determine the length of paths in section 4.2.3, so the operation is allowed, because switches E2-QB1, E2-QA1 and E1-QB10 couple directly the same busbar sections (rule a).

Example 2: In figure 5.21 sectionalizers E2-QB11 and E2-QB21 are closed. Switches of coupling E1, E1-QB1, E1-QA1 and E1-QB2 are closed. In feeder E3 switches E3-QB1, E3-QB2, E3-QA1 and E3-QB9 are also closed. Switches E3-QB1 and E3-QB2 are only allowed to be closed because the busbar sections are coupled and the busbars are coupled with feeder E1. Therefore the marked path with the dashed line is not allowed to be opened with switch E2-QB11 (rule a). The length of this path is five.

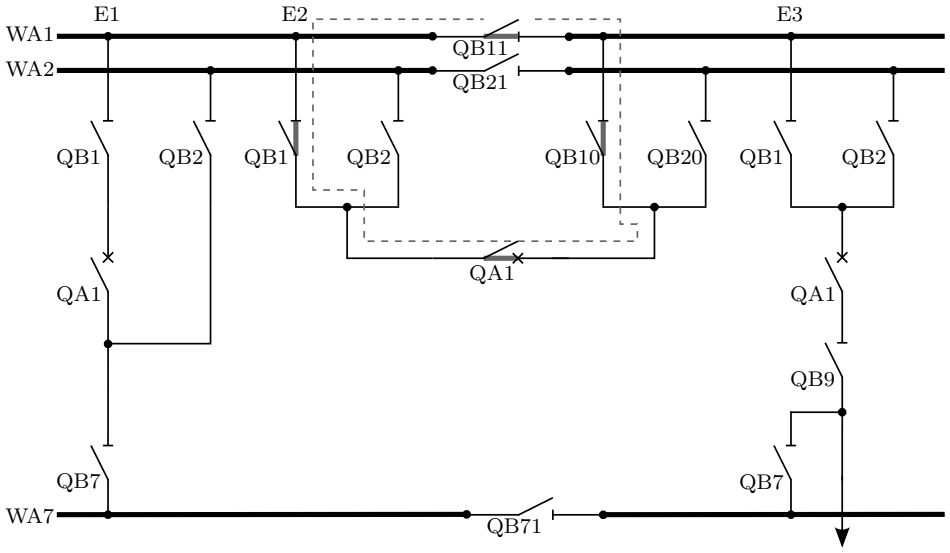


Figure 5.20: Example 1, Parallel path of length 0 (dashed line) allows to open E2-QB11

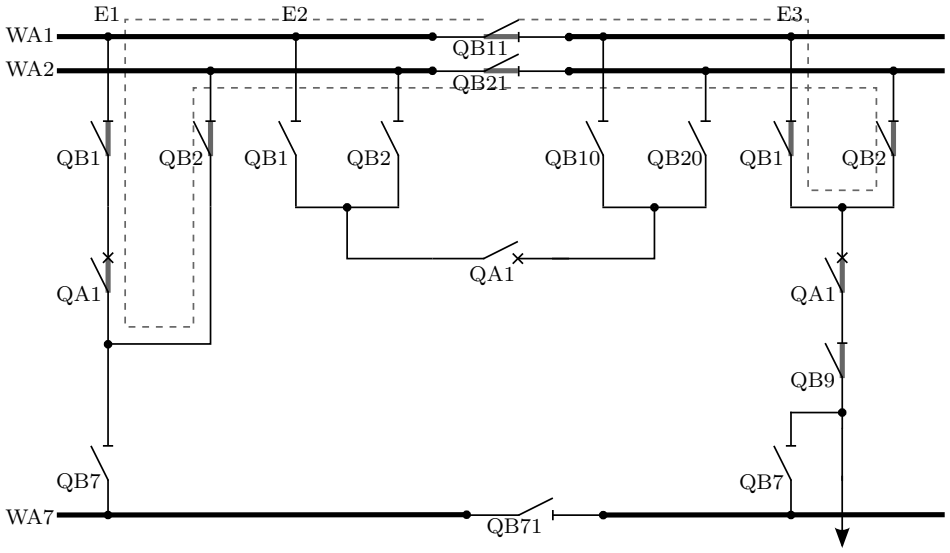


Figure 5.21: Example 2, Parallel path of length six (dashed line) does not allow to open E2-QB11

Example 3: In figure 5.22 a configuration is given in which E2-QB11 is part of a path that passes the auxiliary busbar. In coupling E1 switches E1-QB1, E1-QA1 and E1-QB7 are closed and in feeder E3, switches E3-QB1, E3-QA1 E3-QB9 and E3-QB7 are closed. Furthermore switches E2-QB11 and E2-QB71 are closed. Switch E2-QB71 has a length of zero so that these eight switches on the parallel path have a length of seven. The parallel path for switch E2-QB11 is marked with a dashed line. Opening the switch E2-QB11 would disconnect two main busbar sections that would afterwards only be coupled with the auxiliary busbar. Auxiliary busbars are normally designed to carry the current of one feeder and not the current of the entire substation so that opening switch E2-QB11 is not allowed (rule a).

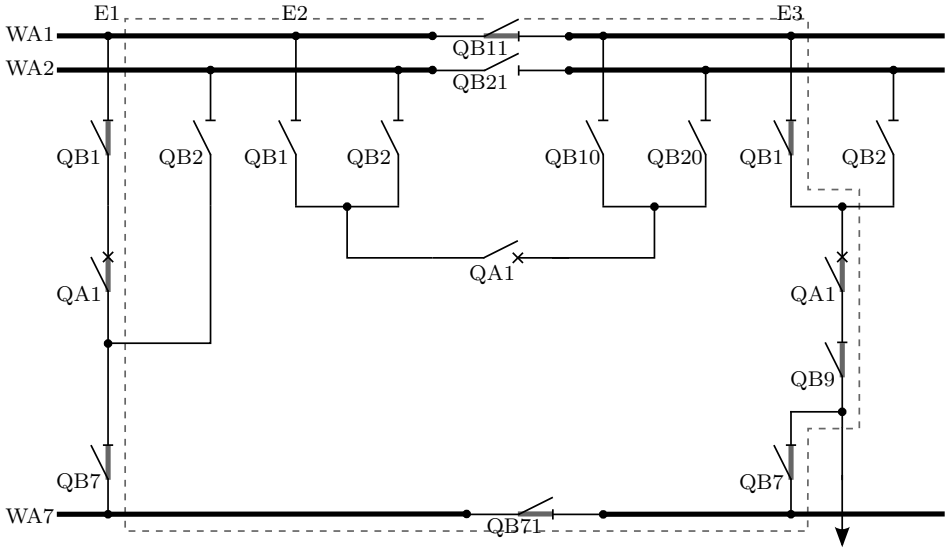


Figure 5.22: Example 3, Parallel path of length 7 (dashed line) does not allow to open E2-QB11

Shunt Disconnector

Shunt disconnectors (DIS-F-SD) are only allowed to be opened or closed if a parallel path across the feeder circuit breaker exists. This means that:

(a) Opening or closing a shunt disconnector is allowed if the length of the parallel path is three. The length of three includes one feeder disconnector (DIS-F), one bypass disconnector (DIS-F-Y) and one feeder busbar disconnector (DIS-F-BB). An example is presented in figure 5.23 showing a parallel path with the length of

three. Parallel path for this switch does not pass a longitudinal coupling because for this length it is closed in the feeder.

Figure 5.23 shows a bay with a shunt disconnector. The parallel path is marked with a dashed line and has a length of three (rule a). Shunt disconnectors are used if no auxiliary busbar is used. If additionally an auxiliary busbar is installed parallel paths are possible, but the length would be longer than three.

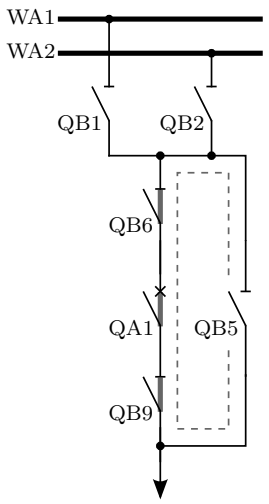


Figure 5.23: Parallel path of length 3 (dashed line) for the operation of a shunt disconnector

Cross-Tie Switch

Cross-tie switches can be used to directly connect two feeders with each other. So it is possible to isolate the busbars for maintenance. Cross-tie switches (DIS-F-CT) are allowed to be closed or opened if a parallel path exists via a coupling. Figure 5.24 shows a configuration with a cross-tie switch. The parallel path with a length of five is marked with a dashed line. The path marked with a dash dotted line passes feeder E3 and E4 and has a length of five as well. To differentiate both paths it is necessary to set the length of the cross-tie switch to zero as described in section 4.2.3. Then the dash dotted path has a length of four and the dashed path has still a length of five. This means for a cross-tie switch that:

(a) Opening or closing a cross-tie switch is allowed if a parallel path with the length of five exists. The length of five includes two coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of a transversal coupling and two feeder busbar disconnectors (DIS-F-BB). Figure 5.24 presents a path (dashed line) with the length of five. Even multiple longitudinal coupling with length zero would not increase the length of the path but are not presented in the figure.

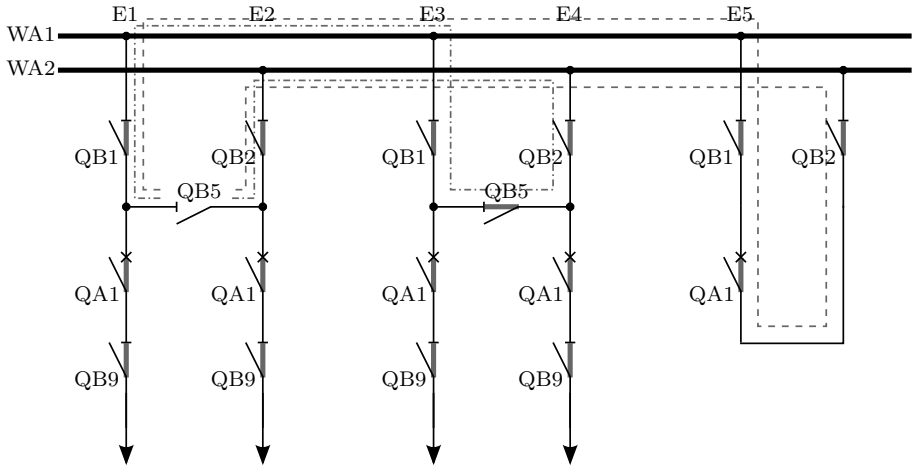


Figure 5.24: Parallel path of length 5 (dashed line) that allows to open or close cross-tie switch

Do Not Energize a Transformer With a Disconnector

Transformers cause an inrush current when they are switched to source even if they are isolated on the other side. This current might damage a disconnector making the connection. With the new introduced potential for transformers and the operational condition "keep the switching sequence" switching the inrush current with a disconnector is prevented for normal substations. If the switching sequence is not given then it has to be ensured for this bay that:

(a) Closing a disconnector in transformer bays (DIS-T-BB) is allowed if potential double: S-I or L-I is detected.

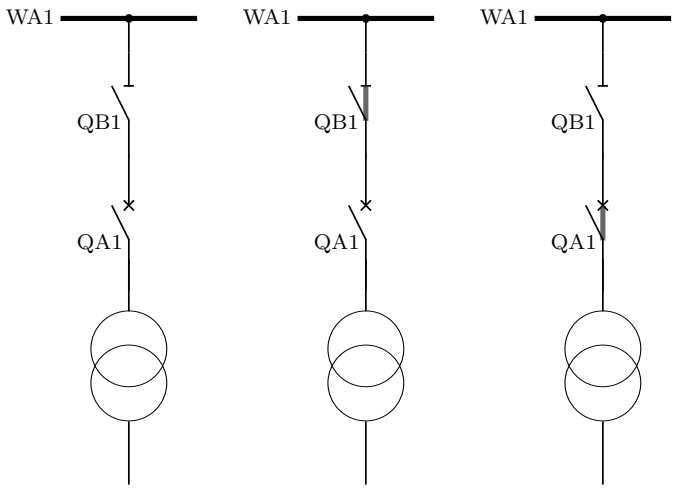
(b) Closing the circuit breaker in a transformer bay (CBR-T) is allowed if potential double: S-S, S-L, L-L, S-T or L-T, is detected.

Figure 5.25 shows two transformer bays.

Example 1: In figure 5.25(a) switch QB1 is open and for switch QA1 the potential double is T-I. For this potential double circuit breakers are not allowed to close if "keep switching sequence" is selected.

Example 2: Figure 5.25(b) shows that QB1 is closed. The resulting potential double for switch QA1 is BB-T which enables closing the circuit breaker and the switching sequence is respected (rule b).

Example 3: But if a situation occurs as it is given in figure 5.25(c) where switch QA1 is closed, then this configuration can be detected, because one side of the switch QB1 has the potential T. Restricting the allowed potential double to S-I and L-I for the operation of DIS-T-BB guarantees that the transformer will not be energized with a disconnector. This forces in this bay to keep the switching sequence (rule a).



(a) Example 1 (b) Example 2 (c) Example 3

Figure 5.25: Transformer bay examples to discuss the switching sequence in this bay

5.1.5 Operational Interlocking Conditions for 2-Breaker Method

The 2-breaker method is able to connect a feeder to both busbars with a specific circuit breaker. But the circuit breakers in bays (CBR-F) are not necessarily built for busbar coupling. If so an extra coupling is needed and switching a feeder from one to the other busbar without interruption is only allowed if a parallel path exists. The following examples demonstrate how to check if closing the circuit breaker is allowed or has to

be interlocked. Figure 5.26 shows a 2-breaker configuration with two feeders E1 and E2 and a coupling bay E3. Feeder E1 is not connected to a busbar but switches E1-QB2 and E1-QB92 are closed. Feeder E2 is connected to busbar WA1 with switches E1-QB1, E1-QA1 and E1-QB91. Additionally switches E2-QB2 and E2-QB92 are closed. The coupling bay connects with switches E3-QB1, E3-QA1 and E3-QB2 busbars WA1 and WA2.

Closing switch E1-QA2 in feeder E1 connects the feeder to busbar WA2. No connection to busbar WA1 exists so no parallel path is needed and closing switch E2-QA2 is allowed (rule a).

Closing switch E2-QA2 in feeder E2 is allowed as well. After closing, the switch E2-QA2 connects both busbars which is allowed because the coupling provides a connection of both busbars too and a parallel path (dashed line) can be detected with the length of eight (rule b).

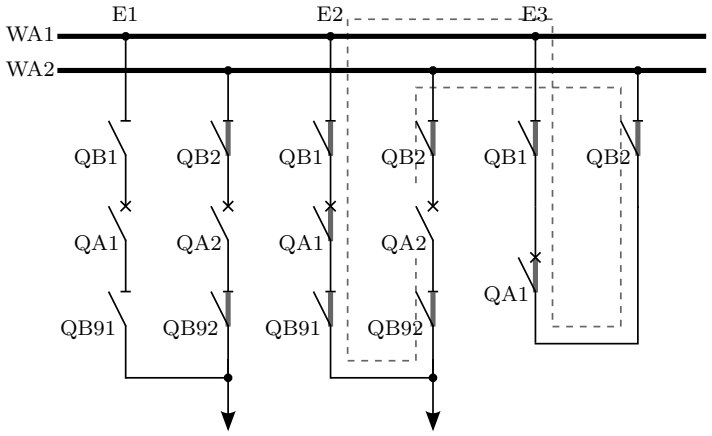


Figure 5.26: Parallel path of length 8 (dashed line) that allows to close switch E2-QA2

Circuit Breaker in Feeder Bay

Because of the considerations above, following conditions have to taken into account:

(a) Closing the circuit breaker CBR-F is allowed if a busbar is only detected on one side of the circuit breaker.

(b) Or closing the circuit breaker CBR-F is allowed if on both sides of the circuit breaker a busbar is detected and a parallel path with the length of eight exists.

The length of eight includes two coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of a transversal coupling, two feeder busbar disconnectors (DIS-F-BB), one feeder circuit breaker (CBR-F) and two feeder disconnectors (DIS-F). Figure 5.26 presents a path (dashed line) with the length of eight. Even multiple longitudinal coupling with length zero would not increase the length of the path but are not presented in the figure.

Circuit Breaker in Coupling Bay

The need of coupling for feeders restricts the operation of circuit breakers in coupling bays (CBR-C) as well.

(a) Opening a coupling circuit breaker CBR-C is allowed if no parallel path exists to not leave any busbars coupled with feeders only.

(b) Except opening a coupling circuit breaker CBR-C is allowed if a parallel path with the length of five exists. The length of five indicates that a second coupling also connects both busbars. Opening the coupling circuit breaker allows to reach selectivity again from a none selective configuration. The length of five includes four coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of transversal couplings.

(c) Closing the circuit breaker CBR-C is allowed if no parallel path with the length of five exists to prevent two parallel couplings and loose selectivity. The length of five indicates that a second coupling connects both busbars. The length of five includes four coupling busbar disconnectors (DIS-C-BB) and one coupling circuit breaker (CBR-C) of transversal couplings.

Do Not Energize a Transformer With a Disconnector

For this type of substation a feeder bay is equal to a transformer bay. Therefore the operational interlocking condition “Keep Switching Sequence” (page 77) ensures that feeders are only connected with the circuit breaker to the busbars. So it is guaranteed that no disconnector has to switch the inrush current.

5.1.6 Operational Interlocking Conditions for 1 ½-Breaker Method

This configuration has in general no extra coupling bay. Therefore coupling of busbars is done with the circuit breakers. For this configuration it is easy to check the number of connections between the busbars. If a connection of both busbars exists already, any other circuit breaker would detected this parallel path. So the number of allowed connections between both busbars can be easily checked with the number of existing parallel paths and therefore be limited by the operator as well. Furthermore it is possible to require for example at least one connection of both busbars. Therefore following conditions have to be checked:

Circuit Breaker in Feeder Bay

(a) Closing a circuit breaker CBR-F is allowed as long as the maximum number of allowed connections between the busbars is lower than the number of parallel paths.

(b) Opening a circuit breaker CBR-F is allowed if the wanted number of parallel paths is still given after opening the switch. In the case that no parallel path exists it has to be checked if the switch would disconnect the busbars.

Do Not Energize a Transformer With a Disconnector

For this type of substation a feeder bay is equal to a transformer bay, similar to the 2-breaker method. Therefore switching the inrush current with disconnectors can be prevented by using the condition "Keep Switching Sequence" (page 77) as well.

5.1.7 Operational Interlocking Conditions for Ring Busbar

For this configuration it can easily be checked if the ring is closed or not, by checking if a parallel path exists or not. Therefore it can easily be implemented to disable closing the ring. For any switch it is just necessary to check if a parallel path would be closed and then interlock the operation. Keep the ring closed can be checked as well, but connecting or disconnecting a feeder requires due to the structure, an opening of the ring. So keeping the ring closed would disable any reconfiguration and is therefore not needed.

Do Not Energize a Transformer With a Disconnector

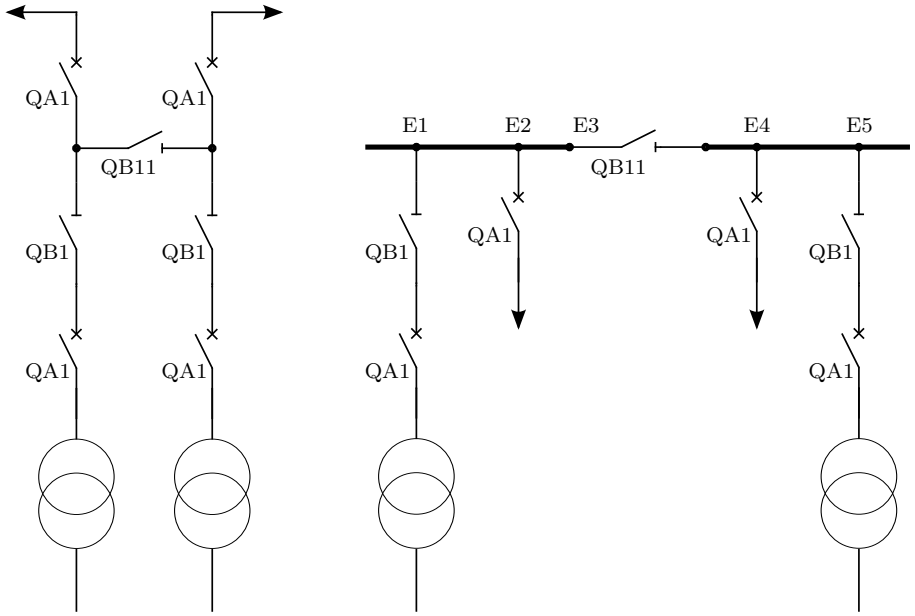
For a ring busbar configuration a transformer is connected with a disconnector to the busbar. To prevent that a disconnector DIS-T-BB or DIS-C-BB has to switch inrush currents it has to be taken into account that:

(a) Closing of DIS-T-BB is only allowed if the potential double: S-BB, L-BB or BB-T is detected.

(b) Closing of DIS-C-BB is allowed if one part of the potential double has the potential I.

5.1.8 Load Center Substation

Topology based interlocking can be used for load-center substations as well, e.g. for so called "H connections". Examples for load-center configurations are given in [2, p. 495]. These configurations can be interpreted as single busbar configurations with one or two busbar sections and two or three feeders for each busbar section. The simple setup has no loops and therefore the evaluation of potential doubles is sufficient for safe operation and it is possible to use the operational interlocking conditions that do not depend on the topology as well. Figure 5.27(a) shows an H connection configuration as presented in [2, p. 495]. Figure 5.27(b) shows the same configuration drawn as a single busbar configuration if the connection points between switches E2-QA1, E3-QB11 and E1-QB1 and E4-QA1, E3-QB11 and E5-QB1 are interpreted as a busbar. Disconnectors to isolate the circuit breakers in the feeder bays E2 and E4 are missing compared to a "real" single busbar configuration but that does not influence topology based interlocking for this configuration.
The use of load disconnectors which are often used in load center substations, is currently not realised in this thesis because only circuit breakers and disconnectors are defined in IEC 61850. But using circuit breakers instead of load disconnectors in the single line diagram allows to use topology based interlocking for normal operation. Earthing can not be realised with this assumption because load disconnectors provide the isolation distance but when they are interpreted as circuit breakers they do not provide the isolation distance. For the operation of earthing switches is another solution needed, for example Boolean equations that allows the operation if all circuit breakers (load disconnectors) are open.



(a) Example of an H connection (b) Example presented in figure 5.27(a) redrawn as single busbar configuration

Figure 5.27: Example of an H connection in a load center substation as presented in [2, p. 495]

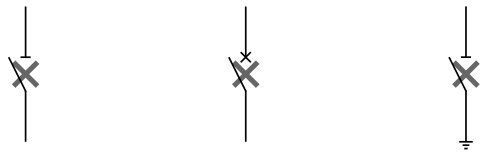
5.1.9 Switches in Fault Position

The described rules above are only taking closed and open switches into account. But it can happen that a switch gets stuck in fault position. Such a switch must not be stressed.

(a) Therefore a switch must not be opened if no extra parallel path to the switch in fault position exists.

(b) And a switch must not be closed if no parallel path exists for the switch in fault position and the new connection would cause a power flow or connect a source to the switch in fault position. Connecting potential doubles S-S, S-L, S-BB, S-T, S-I for a path with a switch in fault position is not allowed.

Figure 5.28 shows how the different switches in fault position are represented in the following figures.



(a) Disconnector in fault position (b) Circuit breaker in fault position (c) Earthing switch in fault position

Figure 5.28: Switches in fault position used in following figures

Example 1: Figure 5.29 shows a configuration with switch E2-QB1 in fault position. Opening switch E1-QB1 is in this configuration allowed. The parallel path (dash dotted line) with switches E1-QB2, E2-QB2 and the switch in fault position E2-QB1 would not allow to open switch E1-QB1 if no other parallel path exists. But the parallel path (dashed line) with switches E1-QB2, E3-QB1, E3-QA1 and E3-QB2 exists and includes no switch in fault position. Therefore opening of switch E1-QB1 is allowed (rule a).

Example 2: Figure 5.30 presents the same configuration as in the previous figure. But in this case opening of switch E2-QB2 is analysed. Both parallel paths (dashed line and dash dotted line) include switch E2-QB1 so that opening of switch E2-QB2 is not allowed (rule a).

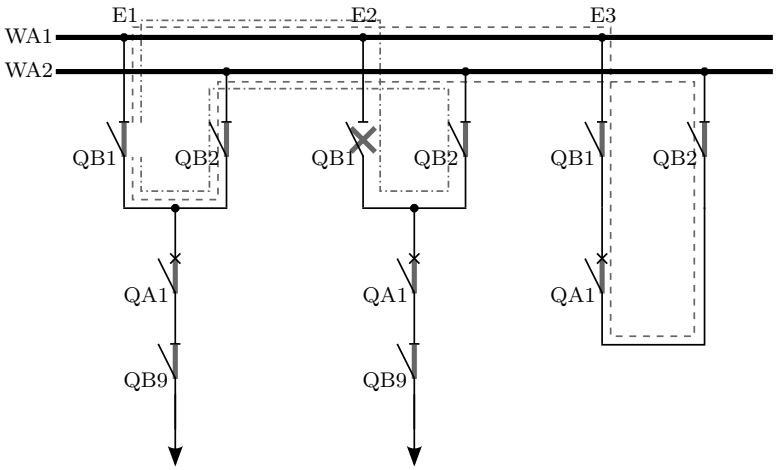


Figure 5.29: Example 1: Fault position of switch E2-QB1 on parallel path (dash dotted line) with an extra parallel path (dashed line) allows to open switch E1-QB1

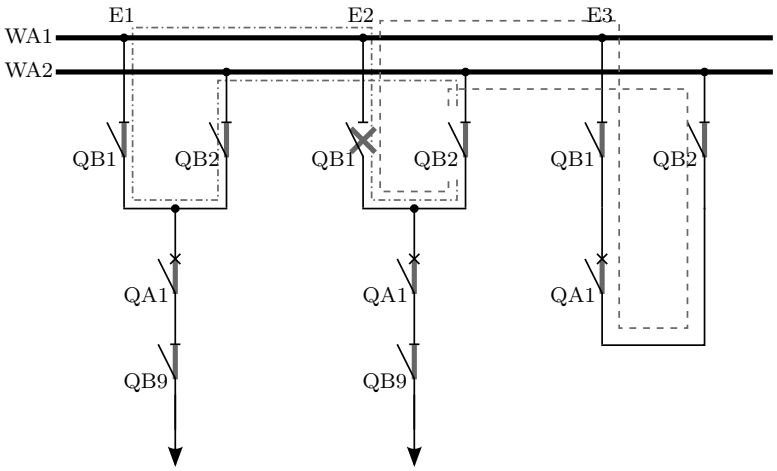


Figure 5.30: Example 2: Fault position of switch E2-QB1 on parallel paths (dash dotted line and dashed line) does not allow to open switch E2-QB2

Example 3: Figure 5.31 shows another configuration in which switch E2-QB1 is in fault position. Closing switch E1-QA1 might cause a power flow threw switch E2-QB1 in fault position and has therefore to be disabled (rule b).

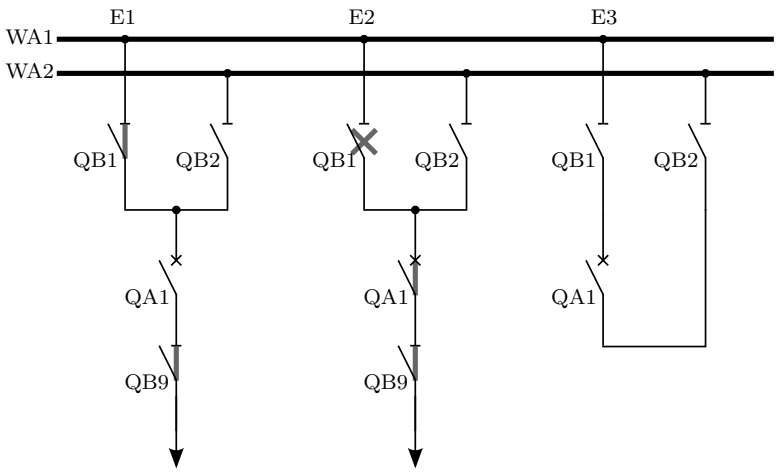


Figure 5.31: Example 3: Fault position of switch E2-QB1 does not allow to close switch E1-QA1

Example 4: Figure 5.32 shows a triple busbar configuration that presents a switch in fault position on a parallel path. This configuration is in normal operation not wanted or allowed, and only used here for demonstration. Modified DFS will in this case not find all parallel paths for switch E1-QB1. If the path marked with the dashed line passing switch E3-QB3 in fault position is found, then the path with the dash dotted line will not be found, or the other way round. But the modified DFS returns the switch in fault position if one is detected. Figure 5.33 shows the same configuration as in figure 5.32. But in this case the parallel paths for switch E3-QB3 are marked with a dashed line and a dash dotted line. Both paths can be detected with DFS for switch E3-QB3. Therefore opening switch E1-QB1 is allowed because after opening the switch, still one parallel path to switch E3-QB3 in fault position exists (rule a).

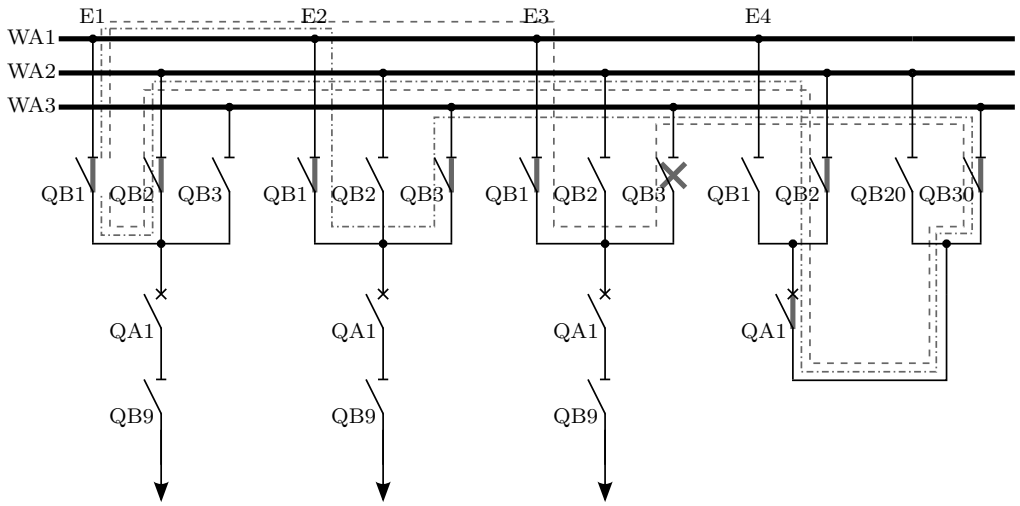


Figure 5.32: Example 4: Fault position of switch E3-QB3 - not all parallel paths found for switch E1-QB1

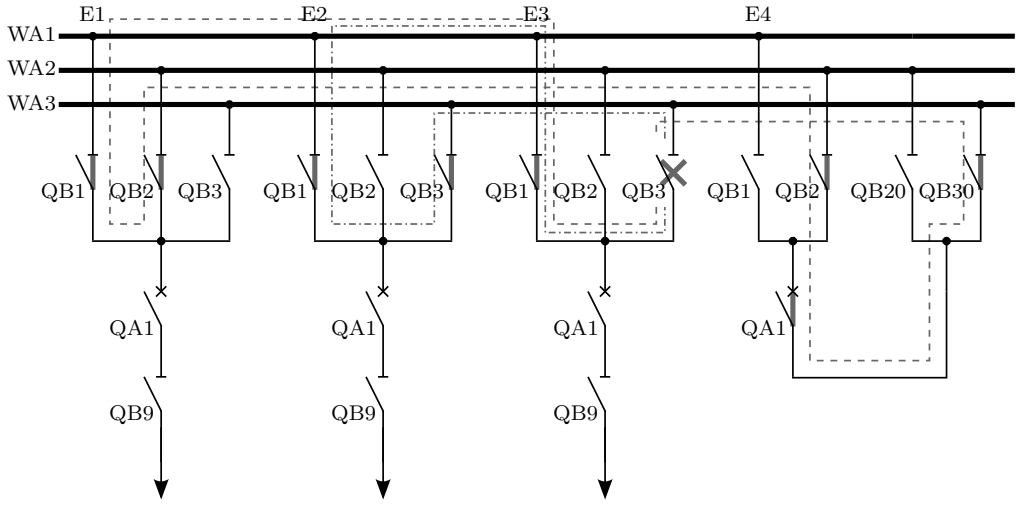


Figure 5.33: Example 4: Fault position of switch E3-QB3 - parallel paths marked for switch E3-QB3

5.2 Reduced Topology

State of the art is to use bay controllers with Boolean equations to realise decentralised interlocking. To implement topology based interlocking in bay controllers it is necessary that a solution performing on bay controller is available. As presented in section 2.3.1, choosing a suitable data format to store the topology is essential to provide a performing solution. But there is still potential for improvement.

Interlocking decisions depend on positions of other switches. The most simple access is to build up a topology representing the entire substation. This is proposed in the papers mentioned in section 3.1 because topology based interlocking is realised with one centralized device. To keep the entire topology always up to date it is required, that all switch positions are known. This means for the realisation in bay controllers, that all switch positions need to be exchanged among all bay controllers. But anyway not all switches are needed for decentralised interlocking, realised in bay controllers. Therefore the proposed solution reduces the topology for decentralised interlocking to needed switch positions only. This has benefits for the use in bay controllers:

- Lower computation time is needed to traverse the topology and therefore to derive interlocking decisions.
- Less memory is needed to store the reduced topology.
- Load on the communication bus is lowered to exchange data between decentralised bay controllers to keep the switch positions of the reduced topology up to date.

To build up the reduced topology it is necessary to distinguish between switches that are needed and switches that are not needed in other bays for interlocking decisions. Therefore criteria are proposed to select switches which are needed for the reduced topology. This means that:

- Bay controllers need information for topology based interlocking of all switches connected to a busbar: DIS-F-BB, DIS-C-BB, DIS-E-BB of any configuration, to know which feeders are connected to the busbar, and which busbars the coupling connects, and to check the isolation distance for busbars.
- And bay controllers need information for topology based interlocking of all switches needed for coupling: DIS-C-BB, CBR-C, and DIS-C of any configuration, for 1 ½-breaker method CBR-F and DIS-F-SD for normal busbar configuration.

- And bay controllers need information for topology based interlocking of all earthing switches in feeder bays connected (DIS-E-FG) to DIS-F-BB and in coupling bays DIS-E-C if forwarding of the earth potential is wanted.

For different substation configurations table 5.1 shows the number of switches for the entire topology and reduced topology of one single bay to give an impression of saving potential as can be seen. Feeders allow significant reduction couplings not.

Table 5.1: Comparison of needed switches for the entire and the reduced topology

substation type	A	B	C	D	E	F
single busbar	5	2	1	5	5	3
double busbar	6	3	2	7	7	5
triple busbar	7	4	3	8	8	4
ring busbar	1	1	1	5	5	3
1 ½-breaker method	15	7	5	-	-	-
2-breaker method	6	4	2	5	5	3

A... number of switches in a feeder with earthing switches

B... number of switches in a feeder needed for reduced topology forwarding earth potential

C... number of switches in a feeder needed for reduced topology not forwarding earth potential

D... number of switches in a coupling with earthing switches

E... number of switches in a coupling needed for reduced topology forwarding earth potential

F... number of switches in a coupling needed for reduced topology not forwarding earth potential

The reduction of the topology demands some prerequisites that are presented in the following. Furthermore examples are presented to estimate saving potential for the reduced topology.

Single, Double and Triple Busbar

For single, double and multiple busbars, inter-bay interlocking requires information of other feeders connected to the busbars and of coupling switches. Figure 5.34 shows a double busbar configuration with earthing switches. Figure 5.35 shows the reduced configuration if forwarding the earth potential is not activated of figure 5.34 for the bay controller in feeder E1. For interlocking decisions of switches in feeder E1 information of switches E2-QB1, E2-QB2, E3-QB1, E3-QB2, E3-QA1, QC11 and QC21 (framed with a dashed line) is needed. If forwarding earth potential with disconnectors is wanted additionally the switches E2-QB5, E3-QB5 and E3-QB6 (framed with dash dotted line) are needed. Not framed switches E2-QA1 and E2-QB9 in bay E2 are not needed for

decisions in bay E1. If switch E2-QB1 or E2-QB2 is closed or both switches are closed it can be assumed that switches E2-QA1 and E2-QB9 will be closed as well. This assumption is used for interlocking with boolean equations as well. If forwarding earth potential with disconnectors is activated it is necessary that earthing switches E2-QC5, E3-QC5 and E3-QC6 are taken into account as well. Otherwise a grounded feeder would be seen as load or source and connecting a source would cause a fault.

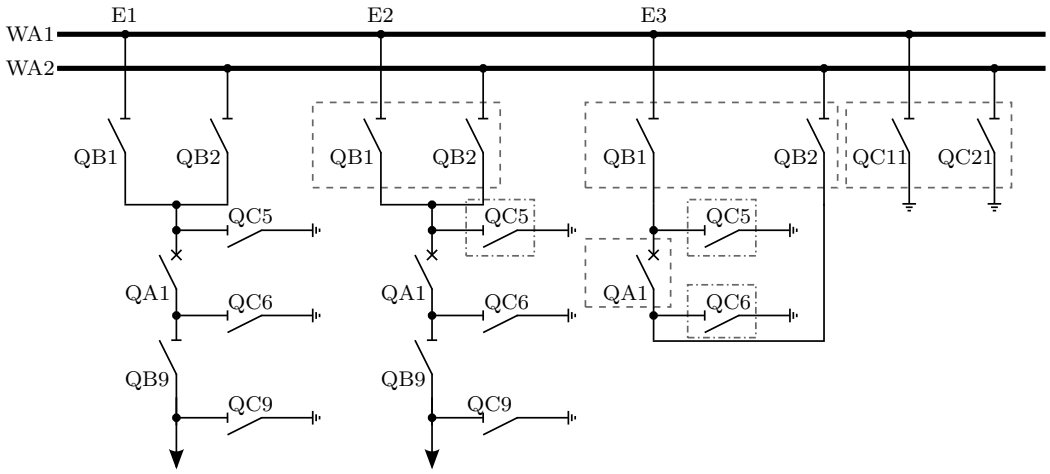


Figure 5.34: Double busbar with marked switches needed for the reduced topology for the bay controller in feeder E1

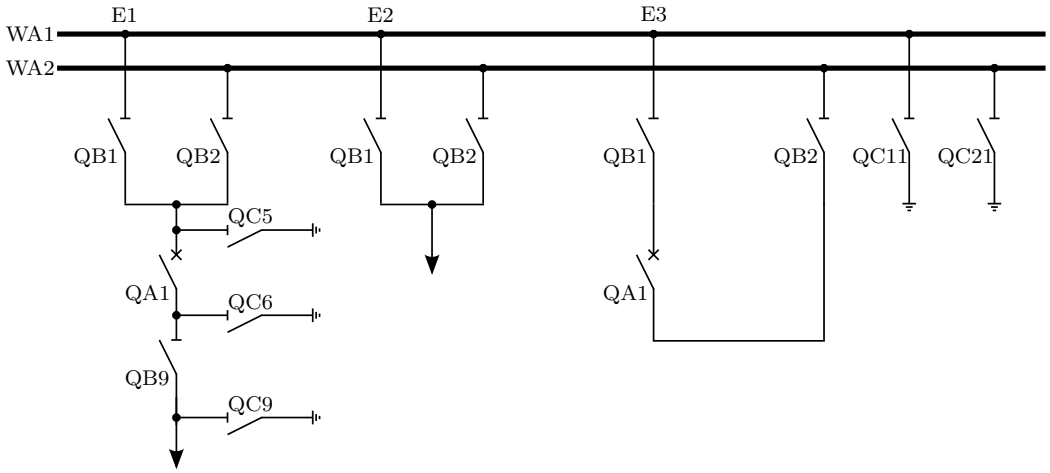


Figure 5.35: Double busbar reduced topology for the bay controller in feeder E1 and not forwarding earth potential with disconnectors

For example: A substation with ten feeders and one coupling has sixty switches in feeders and seven coupling switches and two busbar earthing switches. This results in 69 switches and 35 nodes. The reduced topology for one feeder with forwarding earth potential would have only 42 switches and 15 nodes. The reduced topology for one feeder and not forwarding earth potential would have only 31 switches and 15 nodes. So it can be seen that the topology can be reduced for this example to about fifty percent. This corresponds to an estimated reduction of fifty percent calculation time for traversing the entire graph of such a substation.

Ring Busbar

Due to the topology of a ring busbar it is not possible to significantly reduce the topology. A ring busbar consists of switches connected to a busbar (DIS-F-BB) and coupling switches. In a ring busbar disconnectors in coupling bay are needed to check the isolation distance of the busbar for safe grounding. Only not considering earthing switches in coupling bays can reduce the number of switches in the topology if forwarding the earth potential is not allowed. But the number of nodes is not reduced.

1 ½-breaker method

The 1 ½-breaker method has some potential for reducing the topology. But this is only possible if the switching sequence for disconnectors and circuit breaker is taken into account. This is needed so that the position of a circuit breaker can be used to represent the correct connection of the combination of disconnector - circuit breaker - disconnector. Figure 5.36 shows a 1 ½-breaker configuration. Switches needed for the bay controller in bay E1 are marked. Switches E2-QB1, E2-QA1, E2-QA2, E2-QA3, E2-QB2, E3-QB1, E3-QA1, E3-QA2, E3-QA3, E3-QB2, E3-QC11 and E3-QC21 marked with the dashed lines are needed for the reduced topology. Earthing switches E2-QC1, E2-QC6, E3-QC1 and E3-QC6 are only needed if forwarding earth potential with disconnectors is wanted. E2-QB1, E2-QB2, E3-QB1 and E3-QB2 are needed to check the isolation distance of the busbar. Circuit breakers E2-QA1, E2-QA2, E2-QA3, E3-QA1, E3-QA2 and E3-QA3 are needed for the information which feeder is connected to which busbar and if they couple both busbars. Figure 5.37 presents a reduced configuration of the substation presented in figure 5.36 for bay E1 if forwarding the earth potential is not activated.

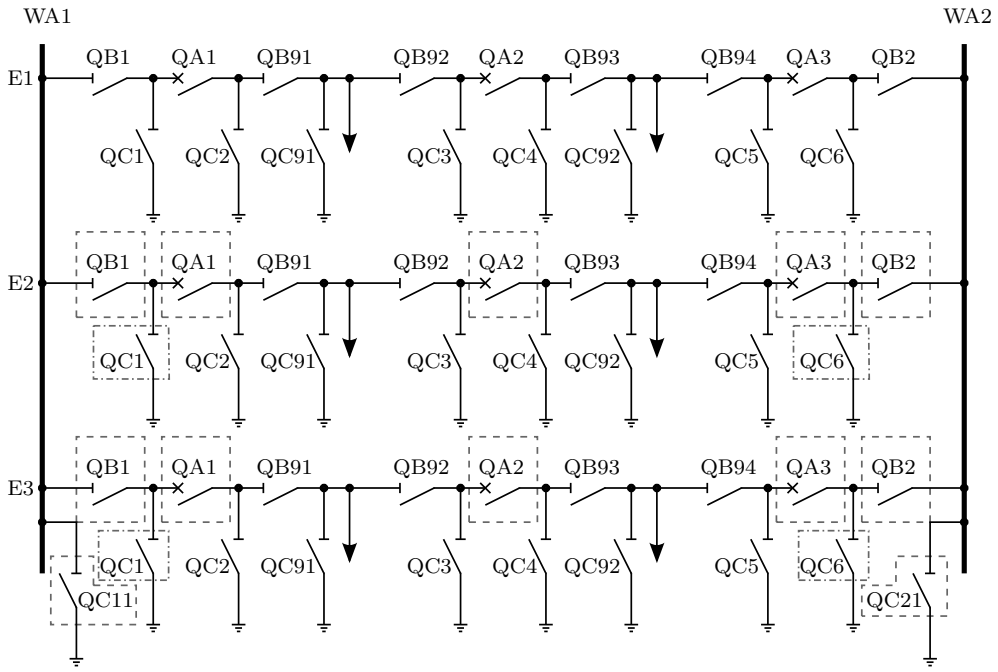


Figure 5.36: 1 ½-breaker method, marked switches needed for bay controller E1

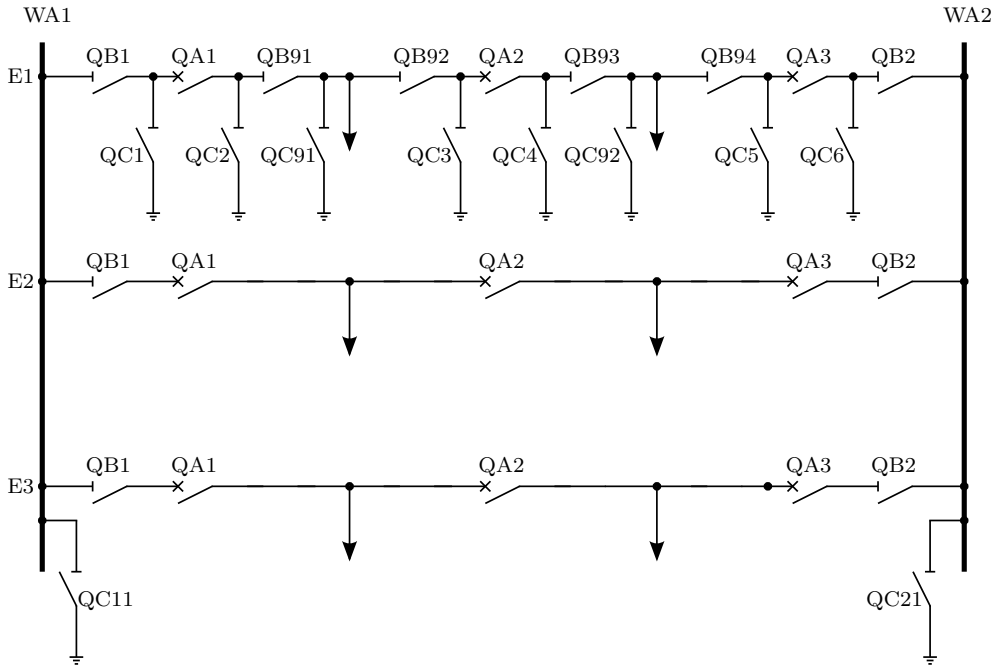


Figure 5.37: 1 ½-breaker method reduced topology for the bay controller E1 not forwarding earth potential with disconnectors

For example: A 1 ½-breaker configuration with ten feeders has 75 switches in feeder bays plus two switches for busbar grounding and 42 nodes. The reduced topology for one bay with forwarding earth potential would have only 45 switches and 26 nodes. If forwarding earth potential is not allowed then the topology is reduced to 37 switches and 26 nodes. For this example a reduction to about fifty percent is possible.

2-Breaker Method

Figure 5.38 shows a two breaker configuration. Switches E2-QB1, E2-QB2, E3-QB1, E3-QA1, E3-QB2, E3-QC11 and E3-QC21 needed for the reduced topology in bay E1 are marked in the figure with a dashed line. Earthing switches E2-QC1, E2-QC2, E3-QC1 and E3-QC2, marked with dash dotted line, are only needed if forwarding earth potential with disconnectors is wanted. This reduction reduces the length of the parallel paths in bays. Instead detecting a length of six between two busbars coupled by the feeder circuit breakers, the length is for the reduced topology only two. But the lengths for switching decisions described in section 5.1.5 for the 2-breaker method are formulated in a way, that the full operation is possible with the reduced topology as well. It is possible to adapt the length of the remaining switches in the reduced bays. Setting the length of the feeder disconnectors to three would not change the length of the parallel paths compared to the not reduced topology but then BFS can not be used to identify the shortest parallel path. Therefore the length of switches is not changed.

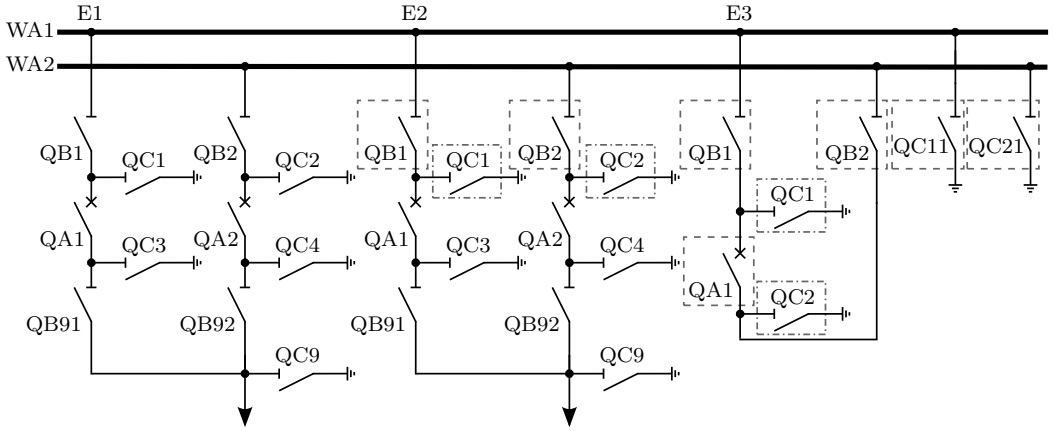


Figure 5.38: 2-breaker method with marked switches needed for the reduced topology for the bay controller in bay E1

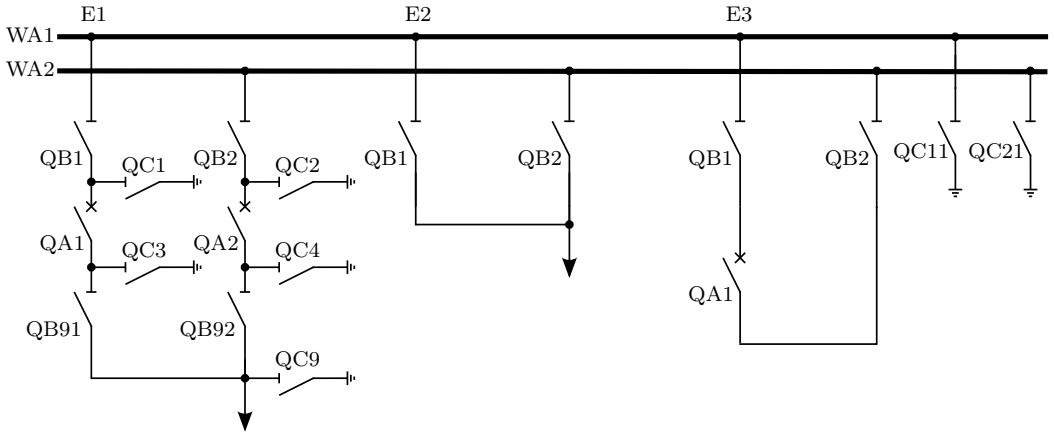


Figure 5.39: 2-breaker method reduced topology for the bay controller in bay E1 not forwarding earth potential with disconnectors

Combined Busbar

Using a combined busbar as auxiliary or transfer busbar does not require any adaptations if the topology is reduced. The relevant parallel paths appear only in the bays. Therefore it is not necessary to adapt the length for the reduced topology.

Shunt Disconnector

A shunt disconnector does not require any adaptations when using a reduced topology. The switch position of this switch is not needed in other bays for interlocking decisions. To enable or interlock the operation of the switch only the existence of the parallel path inside the bay is important. Therefore no adaptations are necessary for interlocking decisions for a reduced topology.

Auxiliary Busbar

Contrary to the combined busbar adaptations for the length of parallel paths are needed for the auxiliary busbars. As presented in figures 5.8 and 5.10 the parallel paths are passing two bays. Figure 5.40 shows a reduced topology for feeder E1, using the auxiliary busbar as auxiliary busbar. The dashed line marks the allowed parallel path (rule b). Compared to figure 5.8 the path is now two switches shorter. When using the auxiliary busbar as auxiliary busbar, then it has to be taken into account that:

(a) Closing DIS-F-Y in the reduced topology is allowed if no parallel path exists and no other switch is connected to the auxiliary busbar.

(b) Or closing DIS-F-Y in the reduced topology is allowed if exactly one parallel path exists with the length of five, so that it is guaranteed that the path does not passes two main busbars and only one DIS-F-Y is connected to the auxiliary busbar. The length of five includes one bypass switch (DIS-F-Y) and two busbar disconnectors (DIS-F-BB), one feeder circuit breaker (CBR-F) and one feeder disconnector (DIS-F). Figure 5.40 presents a path with the length of five. Even multiple longitudinal coupling would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

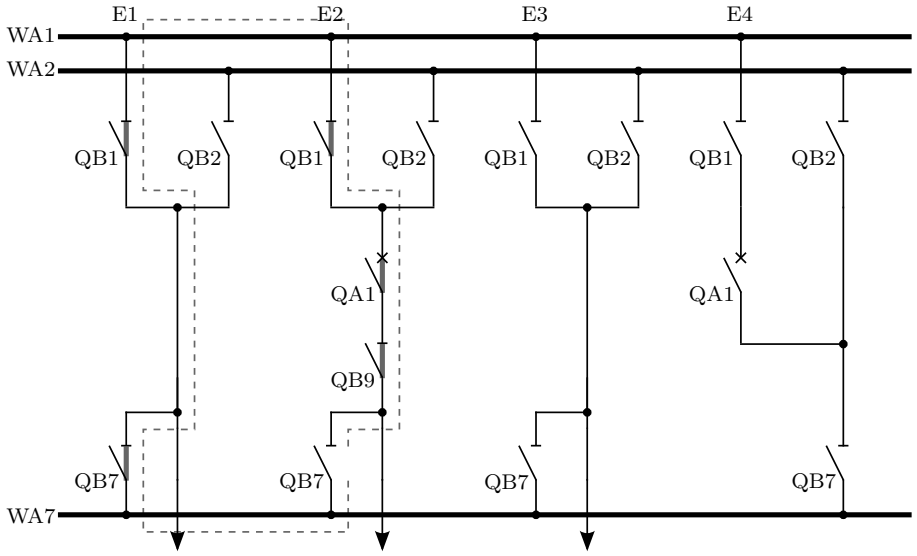


Figure 5.40: Example for a reduced topology using auxiliary busbar, marked parallel path for switch E2-QB7 with the length of five (dashed line)

Figure 5.41 shows a reduced topology for feeder E1, using the auxiliary busbar as transfer busbar. The dashed line marks the allowed parallel path.
Compared to figure 5.10 the parallel path did not change for feeder E1. Figure 5.42 shows a reduced topology for coupling E4, using the auxiliary busbar as transfer busbar. The dashed line marks the allowed parallel path (rule a). In this case the length of the parallel path is two switches shorter compared to the full topology presented in figure 5.10. When using the auxiliary busbar as auxiliary busbar, this means that:

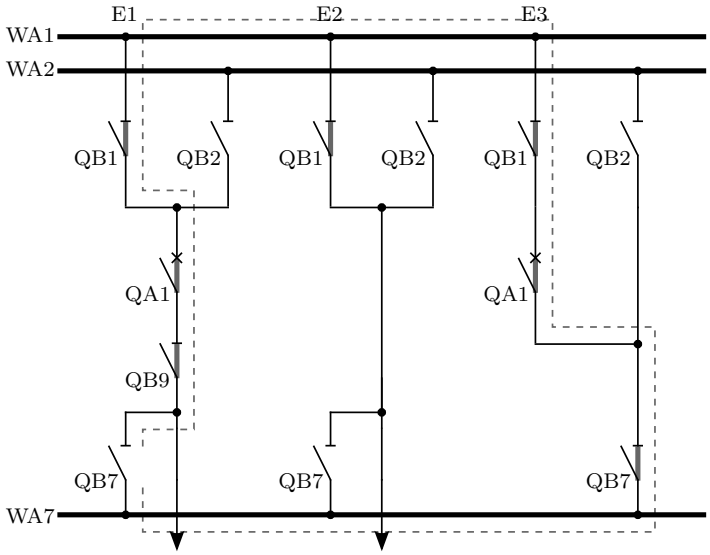


Figure 5.41: Example for a reduced topology, transfer busbar, marked parallel path for switch E1-QB7 with the length of six (dashed line)

(a) Closing CBR-C in the reduced topology is allowed if the coupling is connected to the auxiliary busbar and exactly one parallel path with the length of four exists, so that it is guaranteed that the path does not pass two main busbars and the feeder has to be connected first to the busbar. The length of four includes one feeder busbar disconnector (DIS-F-BB), one bypass switch (DIS-F-Y) and two coupling busbar disconnectors (DIS-C-BB). Figure 5.42 presents a path with the length of four. Even multiple longitudinal coupling would not increase the length of the path and are allowed on the parallel path but are not presented in the figure.

It is possible to adapt the length of the remaining switches (DISFY) in the reduced bays but as mentioned for the 2-breaker method changing the length does not allow to use BFS to identify the shortest parallel path. To avoid this the length of switches is not changed.

If forward earth potential for an auxiliary busbar configuration is chosen then reducing the topology does not bring great benefits. Only circuit breakers would not be needed for the reduced topology and the saving potential is low. The length of parallel paths needs to be adapted and the paths presented in this sections that are two switches shorter would then only be one switch shorter compared to the not reduced topology.

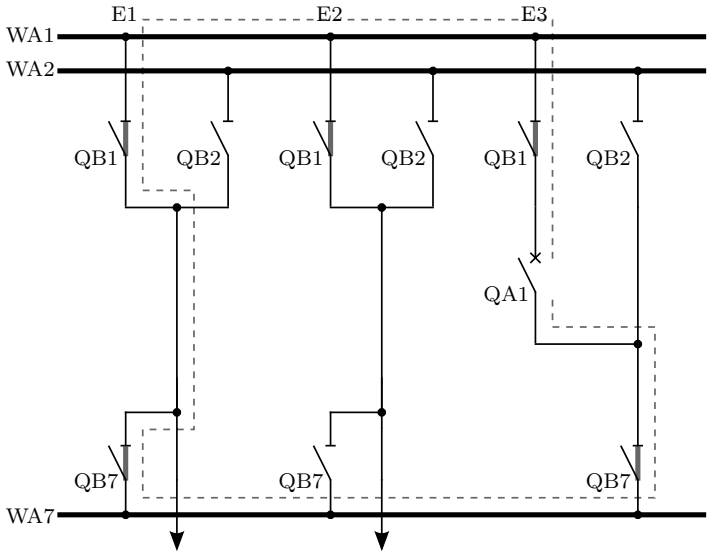


Figure 5.42: Example for a reduced topology using transfer busbar, marked parallel path for switch E3-QA1 with the length of four (dashed line)

5.3 Realisation

This sections presents solutions to improve the usability of topology based interlocking. A program developed in this thesis is introduced and the functions are presented. Necessary steps to realise topology based interlocking are listed and the flow chart to deliver interlocking decisions is given.

5.3.1 New Solutions

Standard IEC 61850

As described in section 3.2.2 none of the solutions in the cited literature uses a standard to describe the topology of a substation. Proprietary solutions to describe the topology do not guarantee interoperability. Bur for the realisation in this thesis the standard IEC 61850 is used to describe, exchange and configure the topology. Figure 5.43 shows a single busbar configuration to describe the needed information for topology based interlocking. An Intelligent Electronic Device (IED) is in this case a bay controllers with protection function. Switches E1-QB1, E1-QA1 and E1-QB9 are assigned to IED1, which is marked with the dashed lines to IED1 in the figure. Switches in feeder E2 are assigned to IED2 and switches in feeder E3 are assigned to IED3. To provide redundancy

IEDs can be used to deliver enable or interlocking signals based on the current topology. Therefore each IED needs the switch positions that are assigned to the other IEDs in the substation as well. To send for example switch position of switch E1-QB1 to IED2 and IED3 communication is needed, which is marked in the figure with the dash dotted line.

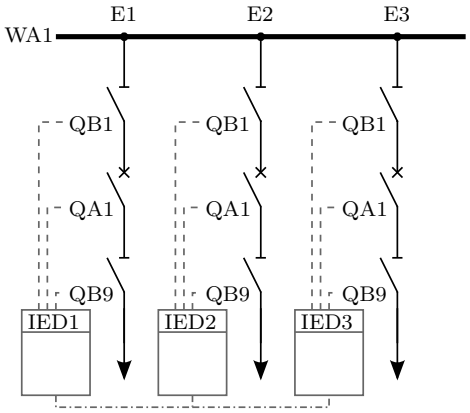


Figure 5.43: Single busbar configuration with IEDs and assignment of devices (dashed lines) and communication line between IEDs (dash dotted line)

Standard IEC 61850 [6] provides with the Substation Configuration Language (SCL) the standardised Substation Configuration Description (SCD) the needed information. The SCD contains [7, p. 134]:

- Description of the single line diagram and the electrical connection of the substation devices
- IED description
- Assignment of substation devices to the IEDs
- Communication description

The above list shows that the standard provides with the SCD suitable information for topology based interlocking. In the following code an example of an SCD-file is presented which was generated with Siemens DIGSI 5 V5.0 for the configuration given in figure 5.43. The entire file has more than ten thousand lines, so only parts needed for topology based interlocking are picked out in this section. The following example is reduced to the root element and the child elements needed for topology based interlocking. Dots indicate that content is skipped at that place.

```
<?xml version="1.0" encoding="UTF-8"?>
<SCL   ... >
   <Private type="Siemens-DIGSI5ExportComment"></Private>
    ⋮
   <Substation name="SingleBusbarExample">   ...   </Substation>
   <Communication>   ...   </Communication>
   <IED configVersion="V04.00.00" type="6MD86" manufacturer="SIEMENS"
       desc="IED1" owner="SingleBusbarExample" name="SIP_IED1">   ...
        </IED>
   <IED configVersion="V04.00.00" type="6MD86" manufacturer="SIEMENS"
       desc="IED2" owner="SingleBusbarExample" name="SIP_IED2">   ...
        </IED>
   <IED configVersion="V04.00.00" type="6MD86" manufacturer="SIEMENS"
       desc="IED3" owner="SingleBusbarExample" name="SIP_IED3">   ⋮
        </IED>
    ⋮
</SCL>
```

Most elements have a “Private” element to store manufacturer-specific information that is not defined by the standard IEC 61850. The element “Substation” includes the topology of the substation. The element “Communication” provides information of the access points of the IEDs. For each IED used in the substation an “IED” element is needed for description.

Redundancy

Redundancy is very important so that in case of an outage of one device, safe operation is still possible in the substation. Previous publications proposed to use a central device to evaluate enable or interlock signals. But one central device does not provide any redundancy, so backup is required. To provide high redundancy using bay controllers to deliver decentralised interlocking is proposed for realisation in this thesis. Bay controllers with protection function are used already to evaluate Boolean equations for decentralised inter bay interlocking. These devices provide enough calculation power, so that they can be used for topology based interlocking as well and provide needed redundancy for interlocking decisions. For example the outage of IED3 as presented in figure 5.44 means that IED1 and IED2 do not get any switch positions from feeder E3. Switches in bay E3 can not be operated any longer in this case. To solve the problem it is proposed in this thesis to store received data and actualise it with current values. Therefore switches in

bay E1 and E2 can still be operated taking the last valid switch positions of switches in bay E3 into account for interlocking decisions. If no values are available of a bay, worst case assumptions are can be used. This means all switches of a feeder bay are closed and all switches of a coupling bay are opened as worst case.

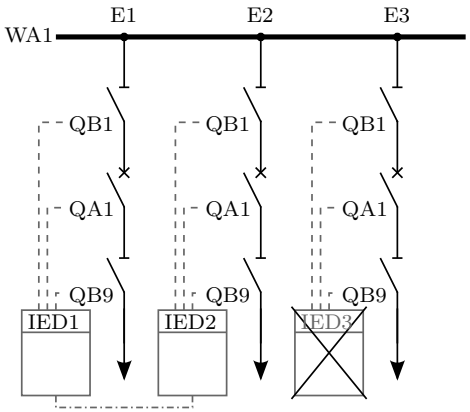


Figure 5.44: Example of the outage of IED3

5.3.2 Program

To demonstrate and test the proposed solutions a program is developed in this thesis. This program provides a Graphical User Interface (GUI) to display the topology and switch positions. The GUI uses the open source software "Piccolo2D"[17] that provides a zoom-able user interface. The program for placing elements in the zoom-able user interface and handling the interaction is developed in this thesis with C# . The C# program hands over commands and switch positions to a developed C++ program, which provides all the functions described in the thesis for automatic topology based interlocking.

When the program C# is started the user is asked to select an SCD-file and then displays the substation configuration stored in this file. Figure 5.45 shows a screen-shot of the GUI for the substation presented in figure 5.43.

Input Needed

The program requires some inputs to provide all features and interlocking conditions discussed in this section.

[17] Available at `https://code.google.com/p/piccolo2d/`

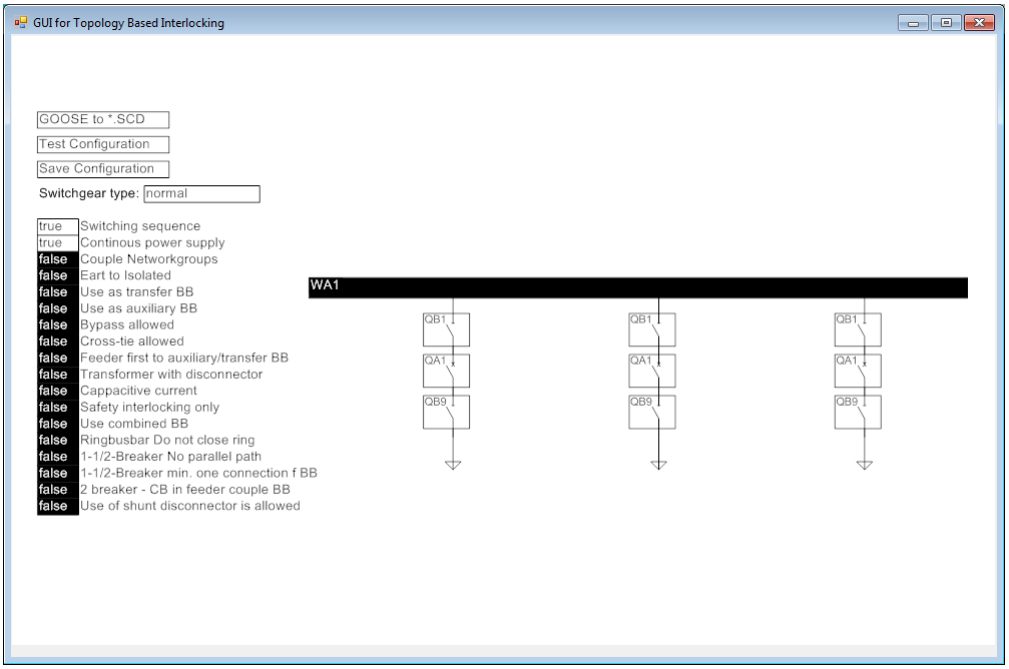


Figure 5.45: Screen-shot of the developed program showing the configuration of the substation in figure 5.43

The topology is needed in form of an **SCD-file**. This file has to be generated with a single line editor that provides the standard IEC 61850. Following tasks have to be performed:

- Place the switches and connect them to represent the substation configuration.
- Place the bay controllers (IEDs)
- Assign the substation devices to the bay controllers (dashed lines in figure 5.43).
- A logic device for each IED has to be added to which the switch positions can be transferred from other IEDs.

The exported SCD file has as previously mentioned a “Substation” element. Following code presents the “Substation” element with its child elements for the substation shown in figure 5.43.

```
<Substation name="SingleBusbarExample">
  <Private type="Siemens_SLESubstation">   ...   </Private>
  <VoltageLevel name="Voltage level1">
```

```
    <Private type="Siemens_SLEVoltageLevel">   ...   </Private>
    <Voltage multiplier="k" unit="V">110</Voltage>
    <Bay name="E1">   ...   </Bay>
    <Bay name="E2">   ...   </Bay>
    <Bay name="E3">   ...   </Bay>
    <Bay name="WA1">   ...   </Bay>
  </VoltageLevel>
</Substation>
```

The substation element has for each voltage level of the substation a "VoltageLevel" element. For the presented example only one voltage level exists. The value of the voltage level is defined in the "VoltageLevel" element with the child element "Voltage", in this example with the value 110 kV. Bays E1, E2 and E3 presented in the example are represented with "Bay" elements as child elements of the "VoltageLevel" element. The busbar WA1 is as well stored in a "Bay" element. This fact makes it possible to differentiate between busbar nodes and nodes in the bays between switches.

Following code presents the "Bay" element of bay E1 with its child elements for the example substation.

```
<Bay name="E1">
  <Private type="Siemens_SLEBay">   ...   </Private>
  <ConductingEquipment name="QB1" type="DIS" virtual="false">   ...
      </ConductingEquipment>
  <ConductingEquipment name="QA1" type="CBR" virtual="false">   ...
      </ConductingEquipment>
  <ConductingEquipment name="QB9" type="DIS" virtual="false">   ...
      </ConductingEquipment>
  <ConductingEquipment name="WB1" type="IFL" virtual="false">   ...
      </ConductingEquipment>
  <ConnectivityNode name="CN2" pathName="SingleBusbarExample/Voltage
     level1/E1/CN2"/>
  <ConnectivityNode name="CN3" pathName="SingleBusbarExample/Voltage
     level1/E1/CN3"/>
  <ConnectivityNode name="CN4" pathName="SingleBusbarExample/Voltage
     level1/E1/CN4"/>
</Bay>
```

The following code presents the content of the "Bay" element with its child elements for the busbar WA1.

```
<Bay name="WA1">
  <Private type="Siemens_SLEBay">   ...   </Private>
```

```
  <ConnectivityNode name="CN_WA1" pathName="SingleBusbarExample/Voltage
      level1/WA1/CN_WA1"/>
</Bay>
```

"Bay" elements have at least one "ConnectivityNode" element. If there is beside the "Private" element only one "ConnectivityNode" element then the "ConnectivityNode" element is identified as a busbar. Bay E1 has four "ConductingEquipment" elements and three "ConnectivityNode" elements. The attribute "type" specifies the type of conducting equipment. So it is possible to identify if it the "ConductingEquipment" is a switch or any other equipment. "DIS" is used to describe a disconnector, "CBR" to describe a circuit breaker and "IFL" to describe a line connected to the feeder in bay E1. Description of other equipment like power transformer, voltage transformer, current transformers or other end nodes of a bay are given in the standard IEC 61850.

The "ConductingEquipment" element of switch E1-QB1 has following structure:

```
<ConductingEquipment name="QB1" type="DIS" virtual="false">
  <Private type="Siemens_SLEConductingEquipment">   ...   </Private>
  <Terminal name="T1" connectivityNode="SingleBusbarExample/Voltage
      level1/WA1/CN_WA1" substationName="SingleBusbarExample"
      voltageLevelName="Voltage level1" bayName="WA1" cNodeName="CN_WA1">
     <Private type="SLETerminal">   ...   </Private>
  </Terminal>
  <Terminal name="T2" connectivityNode="SingleBusbarExample/Voltage
      level1/E1/CN2" substationName="SingleBusbarExample" voltageLevelName
      ="Voltage level1" bayName="E1" cNodeName="CN2">
    <Private type="SLETerminal">   ...   </Private>
  </Terminal>
  <SubEquipment name="A" virtual="false" phase="A">
    <LNode lnClass="XSWI" iedName="SIP_IED1" lnType="
        SIPROTEC5_LNType_XSWI_Ctl" prefix="" lnInst="1" ldInst="Dc1">   ...
         </LNode>
  </SubEquipment>
</ConductingEquipment>
```

The "Terminal" elements are the nodes that the "ConductingEquipment" is connected to. This information is needed to set up the graph of a substation. The "Conducting-Equipments" are the edges of a graph, and the "Terminals" are the nodes of a graph. So it is necessary to read all voltage levels, all bays, all conducting equipment and all connectivity nodes of the "Substation" to set up the entire graph needed for topology based interlocking. Additional the information of the element "LNode" is important.

The attributes of this element describe to which IED the switch is assigned. This information is needed to automatically configure the communication. In this case E1-QB1 is assigned to the IED "SIP_ IED1". The "ldInst" (Logic Device Instance) attribute, "Dc1", is automatically generated in the SCD file and is further used in the SCD to reference to this switch with the IED.

The "Private" elements of the "ConductingEquipment" and the "Terminal" elements provide information for the GUI. Coordinates and the size of the switches, the coordinates of nodes and connection lines are stored in these elements.

Although the standard provides a lot of information additional inputs are needed.

- Busbar numbers and sections, so that the program is able to differentiate longitudinal and transversal busbar coupling. This can be done in the GUI by clicking on the busbar section. The form shown in figure 5.46 pops up and the busbar number and section can be entered.

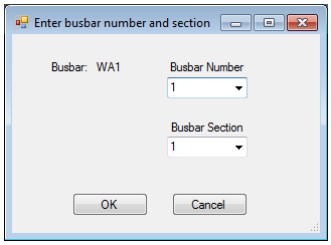


Figure 5.46: Form to enter busbar number and section

- Network groups of the feeders, if this feature is needed.
- Potential of feeders (load or source). By clicking on a feeder in the GUI, the form presented in figure 5.47 pops up, and the network group and the node potential can be entered.

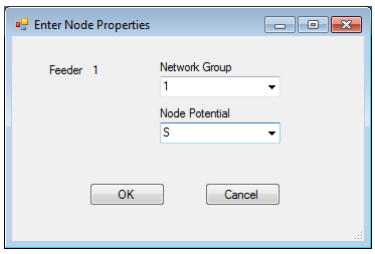


Figure 5.47: Form to enter network group and node potential

- Selected operational interlocking conditions. To set the operational interlocking conditions clicking on any of the rules will show the form presented in figure 5.48 To deactivate all operational interlocking rules at once the option “Safety Relevant only” is included as well.

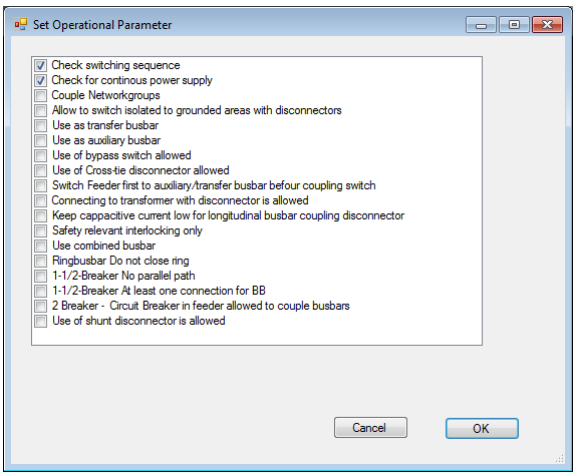


Figure 5.48: Form to select operational interlocking conditions

This additional information is currently not defined in the standard. But the standard is open for future extensions so that it is possible to implement these additions later. Another current available option is to use private elements, which are part of the standard and can be defined by every vendor for special configurations.

Functions Provided

The program provides following functions:

- Identify and verify the selected type of substation by checking the topology. This is needed to guarantee that the proposed algorithm delivers correct interlocking decisions for the topology. Clicking on the box “Test Configuration” in the GUI calls the C++ program to evaluate the topology. Results for the evaluation of the bays are presented in a form. For the single busbar configuration the form with return values is presented in figure 5.49.

- Set up communication. The communication (dashed dotted lines in figure 5.43) to exchange switch positions between the IEDs can be configured automatically.

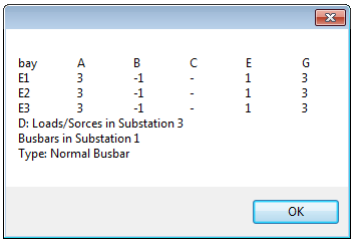


Figure 5.49: Return value of topology check

The program identifies the needed switches for the reduced topology or sets up the communication for all switches by using Generic Substation Events (GSE) with Generic Object Oriented Substation Events (GOOSE) messages. Therefore the SCD-file has to be edited and entries for the communication are added. If at this point GSE is not configured then it is necessary to add to the "Communication" element for each access point of the IED a "GSE" element. The following code shows the structure of the "Communication" element and an added "GSE" element for the IED SIP_ IED1. For the other IEDs a "GSE" element has to be added as well.

```
<Communication>
  <SubNetwork name="PN/IE_1">
    <Private type="Siemens-MasterId">211269441290241</Private>
    <ConnectedAP iedName="SIP_IED1" apName="E">
      <Address>   ...   </Address>
      <GSE ldInst="Dc1" cbName="ControlDatasetTopoSIP_IED1">
        <Address>   ...   </Address>
        <MinTime unit="s" multiplier="m">10</MinTime>
        <MaxTime unit="s" multiplier="m">2000</MaxTime>
      </GSE>
    </ConnectedAP>
    <ConnectedAP iedName="SIP_IED2" apName="E">   ...   </ConnectedAP>
    <ConnectedAP iedName="SIP_IED3" apName="E">   ...   </ConnectedAP>
  </SubNetwork>
</Communication>
```

For each IED it is further necessary to define which switches have to be transmitted to the other IEDs. In this case for IED1 the position of disconnector E1-QB1 has to be transmitted. Therefore the element "DataSet" needs to be inserted into the element "LDevice desc='Tr1' inst='Dc1'". Furthermore the element "GSECon-

trol" has to be added as well This defines that the switch position is transmitted. In the element "LDevice desc='UDEF' inst='GOOSE_ IED1'" the inputs from other IEDs have to be defined. Therefore the element "Inputs" with the displayed child elements "ExtRef" have to be added. In this case for the reduced topology input comes from the busbar disconnectors assigned to IED2 and IED3.

```
<IED configVersion="V04.00.00" type="6MD86" manufacturer="SIEMENS"
    desc="IED1" owner="SingleBusbarExample" name="SIP_IED1">
  ⋮
  <AccessPoint desc="Port E" name="E" clock="false" router="false">
    <Server timeout="0">
      ⋮
      <LDevice desc="Tr1" inst="Dc1">
        <Private type="Siemens-MasterId">dfcc29ca-8d15-4312-a1c1-47
            f54c53258b</Private>
        <LN0 desc="Allgemein" lnClass="LLN0" lnType="
            SIPROTEC5_LNType_LLN0_LDevice_Generic" inst="">
          <Private type="Siemens-MasterId">f6abedfd-2975-4f6b-85ff
              -28b4c10157fb</Private>
          <DataSet name="DatasetTopo">
            <FCDA ldInst="Dc1" lnClass="XSWI" lnInst="1" fc="ST"
                daName="stVal" doName="Pos" prefix=""/>
            <FCDA ldInst="Dc1" lnClass="XSWI" lnInst="1" fc="ST"
                daName="q" doName="Pos" prefix=""/>
          </DataSet>
            ⋮
          <GSEControl name="ControlDatasetTopoSIP_IED1" appID="
              SIP_IED1/Dc1/LLN0/ControlDatasetTopoSIP_IED1" confRev="
              1" type="GOOSE" datSet="DatasetTopo"/>
        </LN0>
          ⋮
      </LDevice>
            ⋮
        <LDevice desc="UDEF" inst="GOOSE_IED1">
        <Private type="Siemens-MasterId">9653ceed-5401-4fcc-9eb3-
            b37cbfdc8733</Private>
        <LN0 desc="Allgemein" lnClass="LLN0" lnType="
            SIPROTEC5_LNType_LLN0_LDevice_Generic" inst="">
            ⋮
          <Inputs>
```

```
            <ExtRef iedName="SIP_IED2" lnInst="1" ldInst="Dc1"
    lnClass="XSWI" doName="Pos" daName="stVal" srcCBName="
    ControlDatasetTopoSIP_IED2" srcLNClass="LLN0" srcLDInst="Dc1"
    serviceType="GOOSE"/>
            <ExtRef iedName="SIP_IED2" lnInst="1" ldInst="Dc1"
                lnClass="XSWI" doName="Pos" daName="q" srcCBName="
                ControlDatasetTopoSIP_IED2"/>
            <ExtRef iedName="SIP_IED3" lnInst="1" ldInst="Dc1"
                lnClass="XSWI" doName="Pos" daName="stVal" srcCBName=
                "ControlDatasetTopoSIP_IED3" srcLNClass="LLN0"
                srcLDInst="Dc1" serviceType="GOOSE"/>
            <ExtRef iedName="SIP_IED3" lnInst="1" ldInst="Dc1"
                lnClass="XSWI" doName="Pos" daName="q" srcCBName="
                ControlDatasetTopoSIP_IED3"/>
          </Inputs>
        </LN0>
      </LDevice>
        ⋮
    </Server>
  </AccessPoint>
</IED>
```

- Deliver interlock or enable signals. The program delivers for the current topology and selected operational interlocking conditions enable or interlock signals. If the operation of a switch is allowed the form presented in figure 5.50 pops up on the screen. If the operation is not allowed, then the reason for interlocking is presented

Figure 5.50: Form with decisions “allowed” and to change switch position

in the form. Figure 5.51 shows the reason of a safety relevant interlock signal. In this case the potential double does not allow to operate the switch. Figure 5.52 shows the reason of an operational interlock signal. The switching sequence does not allow to operate the switch.

Figure 5.51: Form with decisions “Safety interlock” and to change switch position

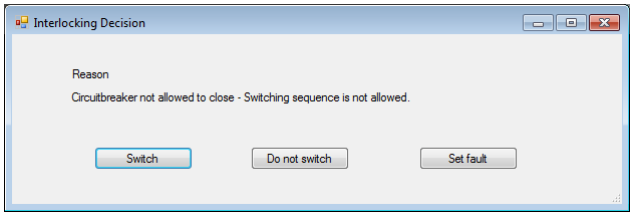


Figure 5.52: Form with decisions “Operational interlock” and to change switch position

- The GUI allows to set each switch to open, closed or fault position to test any possible configuration. Clicking on any switch delivers the interlocking decision. Different reasons are presented in figure 5.50, 5.51 and 5.52. In this forms the buttons “Switch”, “Do not switch” and “Set fault” are available. Independent on the interlocking decisions it is possible to change switch position in the GUI to even test interlocking conditions with configurations that can not be reached with interlocked operation.
- For the use of interlocking conditions with the GUI the option to save the configuration is added as well. This allows to save the current configuration to a file, with all switch positions, selected operational interlocking conditions and added additional input (e.g. node properties ...) by clicking on the box “Save Configuration”. To reload the configuration, the saved file can be selected instead of an SCD-file when the GUI is started.

Set Up a New Substation for Topology Based Interlocking

To set up a new substation or after changing the configuration of an existing substation, it is needed to set up the communication:

1. Draw the substation single line diagram with a suitable program
2. Generate an SCD-file

3. Inputs of substation type and operational conditions are needed
4. Check validity of the topology stored in the SCD-file.
5. If the topology check is positive edit the SCD-file and add the communication for IEDs.

Afterwards the bay controllers can be configured:

1. Open the SCD-file with an suitable IED-configuration tool.
2. Inputs of substation type, network group, potential of feeder, and operational conditions are needed
3. Check validity of the topology stored in the SCD-file.
4. Create a CID-file to configure the IEDs
5. Check validity of the topology in the device stored in the CID-file.
6. Build up the adjacency matrix for the (reduced) topology.

Finally following functions are needed in the IED:

- First start up of device:
  1. Check validity of the topology in the device stored in the CID-file.
  2. Build up the (reduced) topology for the device.
- Continuous operation:
  1. Actualize the topology with current switch positions.
  2. Deliver enable or interlock signals for the switches assigned to the IED.

Flow Chart

The flow chart in figure 5.53 shows how modified search strategies are used to deliver interlocking decisions in the developed program. Before starting with any search strategy it is necessary to update the length of switches in coupling bays. This guarantees that the modified search strategies BFS and DFS are able to deliver the correct length of parallel paths. In the next step modified BFS is used to search the graph of a substation to identify the potential double of the switch or to identify the shortest parallel path. This

information allows to deliver safety relevant interlocking. If safety relevant interlocking delivers an enable signal then operational restrictions are analysed.

For operational interlocking decisions the shortest parallel path can be used to generate interlock or enable signals without searching the entire substation. For example, the shortest parallel path is sufficient to deliver interlock signals if the shortest parallel path is longer than the needed one that would generate an enable signal. Or if a path with any length is detected that is different to the needed one and only one path with a specified length would be allowed the operation, then the shortest parallel path is sufficient to generate an interlock signal as well. Or if any parallel path with a certain length is needed to generate enable signals and this length is discovered with BFS so an enable signal is generated. Therefore it is possible with BFS to generate interlock or enable signals without searching the entire substation using the shortest parallel path for interlocking decisions.

For some decisions the information of other parallel paths is needed as well. In this case modified DFS is needed to identify the further needed parallel paths.

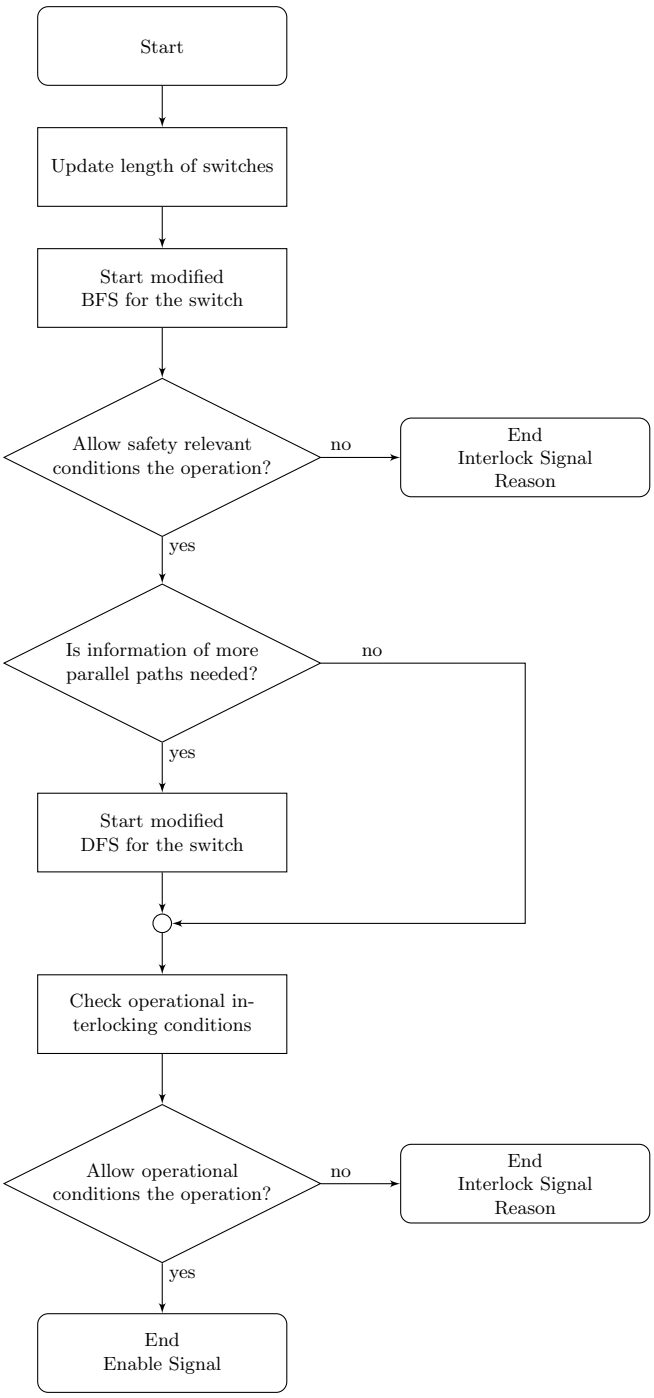


Figure 5.53: Flowchart of the program developed in the thesis to generate interlock or enable signals

6

Automatic Validity Check for Substation Configurations

Safety relevant interlocking is formulated in a way that it does not depend on the topology. But operational interlocking conditions depend very much on the topology. For different configurations different criteria need to be applied. To ensure that search strategies and interlocking decisions are valid for the substation, verification of the topology is essential. Following sections 6.1 to 6.3 propose to use algorithms to verify the topology. The original algorithms are well known in graph theory. New in this thesis is to apply them for testing topology of a substation and to perform adaptations to use the algorithms for this test. This is proposed and discussed in the next sections. The validity check is done with following algorithms:

- Transitive closure is used to test the reachability in a substation. If it is not possible to reach all other nodes from any node in the substation, a failure in the topology of a substation is for sure given. Therefore reachability is absolutely needed for topology based interlocking in substations.

- If reachability is given, BFS can be used to check the number of switches in a feeder or coupling. Further criteria as the distance of load or source to busbar is checked to detect missing or additional switches as well with BFS. So it is possible to differentiate between configurations that allow full safety relevant and operational interlocking, configurations that need DFS for operational interlocking because BFS will not find reliably the shortest parallel path, and unknown configurations for which safety relevant and topology independent operational interlocking can not be automatically provided.

- The test on cycles is done with DFS, to provide necessary information that the switches in bays do not cause cycles. This is necessary because cycles will cause problems for BFS and DFS to identify the required length of parallel paths. If cycles are detected only safety relevant and topology independent operational interlocking can be provided, as for unknown configurations.

6.1 Transitive Closure

The validity of a graph is essential for correct operation of the proposed methods. A simple check on validity of the topology is to check whether all nodes can be accessed in the graph. To investigate if some nodes can not be accessed in the graph, a check of reachability can be done with transitive closure. Transitive closure is defined for directed[18] graphs but can be used for the more general undirected graphs, which are used for substations, as well. A definition of transitive closure is given in [16, p. 33]: With the power of the adjacency matrix it is easy to calculate the transitive closure. If a path exists between two nodes in a graph G with n nodes, then the path has a maximum length of $n-1$ edges. So for a graph G with the adjacency Matrix A and n nodes:

$$S = \sum_{i=1}^{n-1} A^i \tag{6.1}$$

represents the transitive closure. The reachability matrix E is further defined by

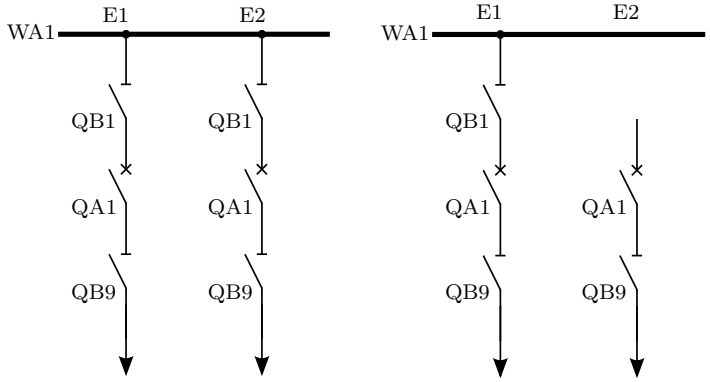
$$e_{ij} = \begin{cases} 1 \; if \; s_{ij} \neq 0 \\ 0 \; if \; s_{ij} = 0 \end{cases} \tag{6.2}$$

where s_{ij} are the elements of S. If a connection from node i to node j exists, the entry e_{ij} is 1. If an entry e_{ij} of the reachability matrix is zero, then node i and node j have no connection in the graph. This means:

- If any entry e_{ij} is zero then it is not possible to reach all nodes even if all switches are closed and so topology based interlocking can not be applied to the substation configuration.

[18] Edges have a direction and can only be discovered in this direction. Undirected edges can be discovered in both directions

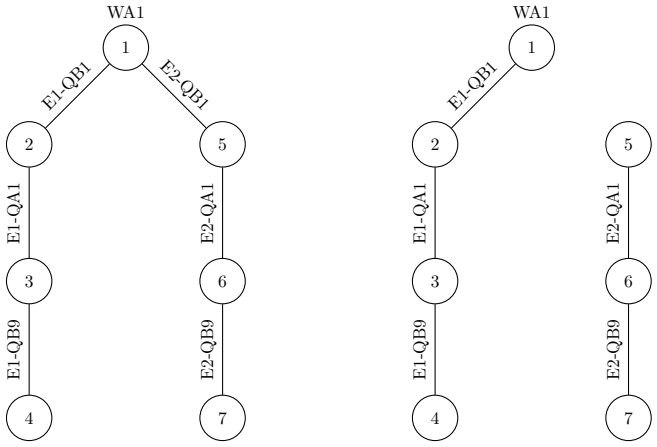
Earthing switches must not be taken into account for the transitive closure in substations because the earth node might connect possibly separated areas. A simple configuration is chosen to show how transitive closure can be used for checking the topology in a substation. Figure 6.1 shows a single busbar configuration with two feeders only, so that the number of nodes is readily comprehensible. Figure 6.1(b) shows a configuration that misses switch E2-QB1 compared to the substation in figure 6.1(a).



(a) Example of a single busbar with two feeders and all normally used switches

(b) Example of a single busbar with two feeders. Compared to 6.1(a) switch E2-QB1 is missing

Figure 6.1: Example of a single busbar configuration to test the validity of the graph



(a) Graph $G1$ of the switchgear shown in figure 6.1(a)

(b) Graph $G2$ of the switchgear shown in figure 6.1(b)

Figure 6.2: Graph of the switchgears shown in figure 6.1

Figures 6.2(a) and 6.2(b) show graphs of the substation presented in figure 6.1. The nodes are numbered inside the circle. These numbers are used to set up the adjacency matrix for graph $G1$ and $G2$, presented in equation 6.3. The transitive closure for graph $G1$ and the reachability matrix is given in equations 6.4. For graph $G1$ all nodes can be reached within the graph. The transitive closure for graph $G2$ and the reachability matrix is shown in equations 6.5. It can be seen that for graph $G2$ not all nodes can be accessed within the graph from any starting point. Nodes 1, 2, 3, and 4 can reach each other, but nodes 5, 6 and 7 can not be reached. Nodes 5, 6 and 7 can only be reached starting from one of these nodes. This is of course due to the fact, that switch E2-QB1 is missing in graph $G2$ and therefore the graph is separated into two parts. One part includes the busbar and nodes of feeder E1 and the other part only nodes inside of feeder E2.

$$A_1 = \begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}, A_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \tag{6.3}$$

$$S_1 = \sum_{i=1}^{6} A_G^i = \begin{pmatrix} 28 & 14 & 19 & 5 & 14 & 19 & 5 \\ 14 & 27 & 13 & 13 & 20 & 6 & 6 \\ 19 & 13 & 21 & 8 & 6 & 7 & 1 \\ 5 & 13 & 8 & 8 & 6 & 1 & 1 \\ 14 & 20 & 6 & 6 & 27 & 13 & 13 \\ 19 & 6 & 7 & 1 & 13 & 21 & 8 \\ 5 & 6 & 1 & 1 & 13 & 8 & 8 \end{pmatrix}, E_1 = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} \tag{6.4}$$

$$S_2 = \sum_{i=1}^{6} A_2^i = \begin{pmatrix} 8 & 8 & 12 & 4 & 0 & 0 & 0 \\ 8 & 20 & 12 & 12 & 0 & 0 & 0 \\ 12 & 12 & 20 & 8 & 0 & 0 & 0 \\ 4 & 12 & 8 & 8 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 7 & 7 & 7 \\ 0 & 0 & 0 & 0 & 7 & 14 & 7 \\ 0 & 0 & 0 & 0 & 7 & 7 & 7 \end{pmatrix}, E_2 = \begin{pmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{pmatrix} \tag{6.5}$$

A further example is given in figure 6.3. This figure shows the same substation as in figure 6.1(b) but with additional earthing switches in feeders E1 and E2. The corresponding graph $G3$ is given in figure 6.4. This example is used to demonstrate why earthing switches have to be ignored for the topology check. In this case graph $G3$ has one more node, the earth node, and four more edges, the earthing switches. Therefore the adjacency matrix given in equation 6.6 has a higher dimension.

$$A_3 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \end{pmatrix} \tag{6.6}$$

The transitive closure is given in equation 6.7. The reachability matrix is given in equation 6.8

$$S_3 = \sum_{i=1}^{7} A_3^i = \begin{pmatrix} 42 & 126 & 117 & 46 & 92 & 102 & 33 & 152 \\ 126 & 311 & 324 & 117 & 254 & 277 & 102 & 437 \\ 117 & 324 & 311 & 126 & 254 & 277 & 102 & 437 \\ 46 & 117 & 126 & 42 & 92 & 102 & 33 & 152 \\ 92 & 254 & 254 & 92 & 227 & 256 & 96 & 368 \\ 102 & 277 & 277 & 102 & 256 & 277 & 114 & 414 \\ 33 & 102 & 102 & 33 & 96 & 114 & 39 & 142 \\ 152 & 437 & 437 & 152 & 368 & 414 & 142 & 577 \end{pmatrix} \tag{6.7}$$

$$E_3 = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} \tag{6.8}$$

As one can see, the separated areas detected in graph $G2$ appear now as connected areas in graph $G3$ because the reachability matrix has no zeros. The reason is, that the earthing switches connect both areas via the earth node. The missing switch, that should connect feeder E2 to the busbar can therefore not be detected with the transitive closure. This is the reason why earthing switches have to be ignored when the topology is supposed to be checked on missing switches.

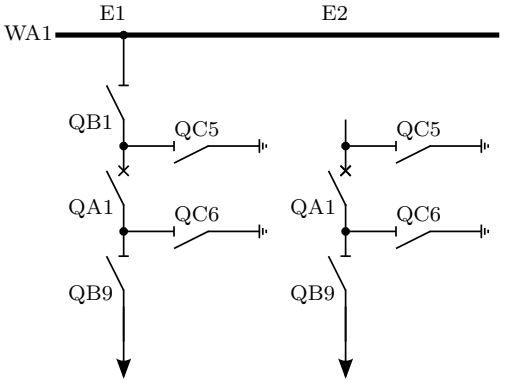


Figure 6.3: Incomplete substation configuration as presented in 6.1(b) but here with earth switches in the feeders

The multiplication of the adjacency matrix is a rather simple formal algorithm to check the reachability of the substation topology. The disadvantage is, that matrix multiplication for a large number of nodes takes a lot of time. This is due to the fact, that the matrix is larger and therefore more multiplications are needed to calculate the transitive closure. If the topology of the substation is taken into account it is possible to reduce the effort to proof reachability. For example a single busbar substation with ten feeders has three nodes in each feeder and one busbar, in sum 31 nodes. The transitive

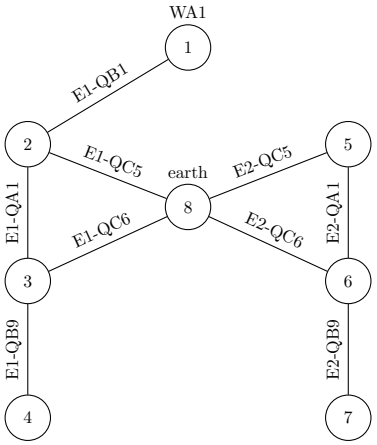


Figure 6.4: Graph $G3$ of the switchgear shown in figure 6.3

closure requires the 30^{th} power of the adjacency matrix as given in equation 6.1. For the example of the single busbar configuration every node can be reached from every other node within a maximum of six edges. Stopping calculation of the equation 6.1 at the 6^{th} power of the adjacency matrix, already delivers a reachability matrix without zero values, in the case that no switch is missing.

[16, p. 495] shows that BFS can be used for transitive closure as well. Therefore, for directed graphs BFS has to search the entire graph for each node of the graph. For undirected graphs, to check for reachability, BFS can be used to start at any node. The number of discovered nodes has to be equal to the number of nodes in the graph to proof reachability. For BFS the earthing switches must not be considered when checking as well. It should be used therefore:

- Matrix multiplication can be used on a computer used to edit the single line editor and automatic configuration of communication relation.
- BFS can be used for checking the reduced topology in bay controllers with protection function.

6.2 Check Number of Switches

Section 6.1 presents a test to check if all nodes in the substation are connected or not. But reaching all nodes in the substation does not guarantee that all necessary switches or to much switches are added to the substation configuration.

Missing Switches

Figure 6.5 shows a double busbar configuration. In bay E1 switch E1-QB1 is missing.

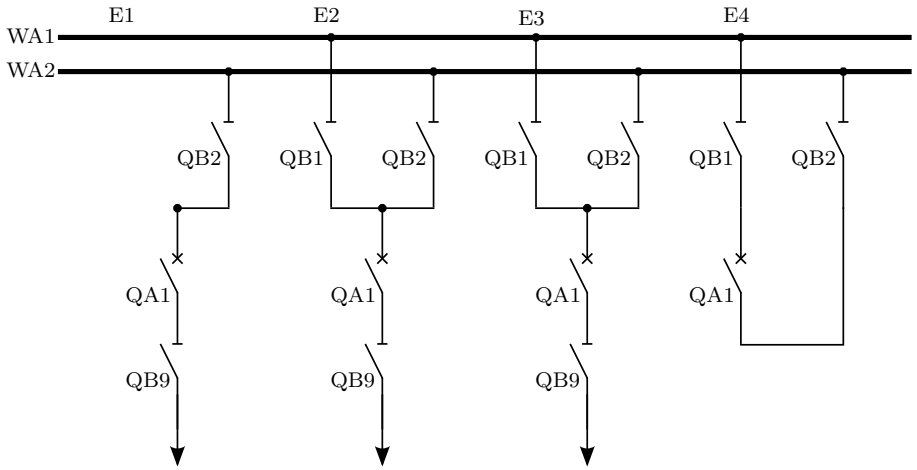


Figure 6.5: Double Busbar configuration with an incomplete bay E1, missing switch E1-QB1

Transitive closure as presented in the previous section is not able to detect that a switch is missing because all nodes can still be reached in the substation. This configuration can be handled with the previous defined interlocking conditions if this switch is intentionally not installed, for example if the feeder E1 is only supposed to get connected to busbar WA2. But if switch E1-QB1 is installed and should be used, then the switch has to be part of the substation configuration. Otherwise the switch can not be included into interlocking decisions. Therefore such a configuration should generate a warning while setting up the substation. To provide a check, table 6.1 can be used. This table extends table 4.1 with an additional criterion. Criteria A to E have been discussed in section 4.1. Criterion G is the sum of switches in a feeder bay excluding the earthing switches. The new criterion G is not suitable to differentiate substation types but provides a check, if the needed number of switches is installed in each bay. For the example given in figure 6.5 criterion G for bay E1 is equal to four. This indicates that one switch might be missing. On the one hand criterion G can be used to check if any switch is missing. On the other hand it can be checked if more switches than necessary are installed, which might be a problem as well.

Table 6.1: Criteria to evaluate validity of the substation (extended table 4.1)

substation type	A	B	C	D	E	G
single busbar	3	-	1-3	2+	1	3
..with auxiliary busbar	1	4	1-3	2+	2	4
double busbar	3	2	1-3	2+	2	5
..with auxiliary busbar	1	2	1-3	2+	3	6
..with shunt disconnector	2	2	1-3	2+	2	6
triple busbar	3	2	1-3	2+	3	6
ring busbar	1	-	3	1	*F	1
1 ½-breaker method	3	9	-	2+	2	9
2-breaker method	3	6	3	2+	2	6

A... number of switches on the shortest path from a load to a busbar

B... number of switches on the shortest path between busbars in a feeder bay

C... number of switches on the shortest path between busbars in a coupling bay

D... number of loads/sources connected to a busbar

E... number of busbars - *F means one busbar for each feeder

G... number of switches in a feeder bay

Additional Switches

Additional switches might require adaptations of the length of switches because they can change the length of the parallel path used for operational interlocking conditions. If additional switches are installed in a position where they do not influence the length of parallel paths, then no adaptations are required (see Example 1). But if they are installed so that they change the expected length of parallel paths then adaptations of the length of this additional switch is needed (see Example 2). An adaptation of the length requires to use DFS to provide the correct length of parallel paths including the shortest path because BFS is no longer suitable to identify the shortest parallel path. Figure 6.6 gives examples where an extra disconnector can be installed.

- Example 1: Disconnector E2-QB6 does not require any adaptations. This switch is needed for shunt disconnectors to isolate circuit breaker E2-QA1. Without the shunt disconnector the switch does not bring benefits. But the switch does not influence the interlocking rules because it does not change the length of any parallel path, and does not influence the potential doubles.

- Example 2: Disconnector E3-QB5 requires some adaptations. The switch in series to disconnector E1-QB1 changes the length of the parallel path. Criterion B can

be used to identify that there is an extra switch between the busbars. It is possible to set the length of the switch to zero so that this bay has the same length between the busbars as the other feeder bays. But as described in section 4.4 BFS is not able to find for sure the shortest path if weighted edges are used. Therefore DFS is needed to provide the correct length of parallel paths including the shortest path.

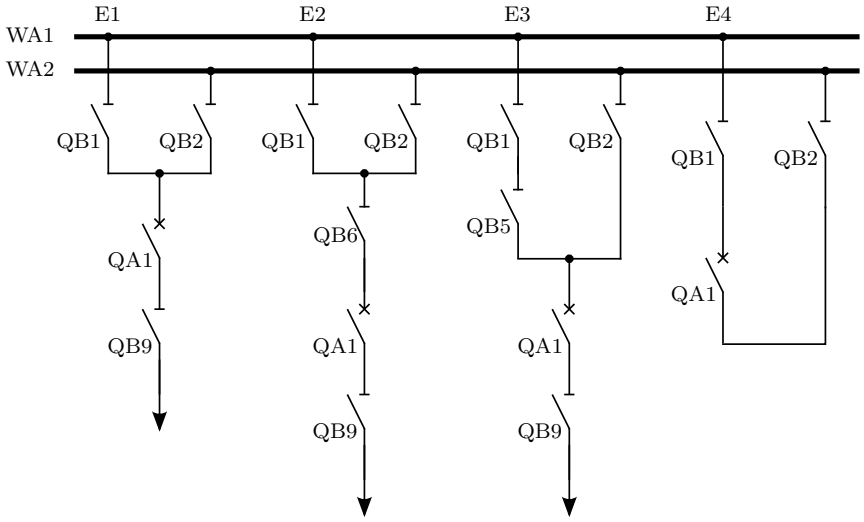
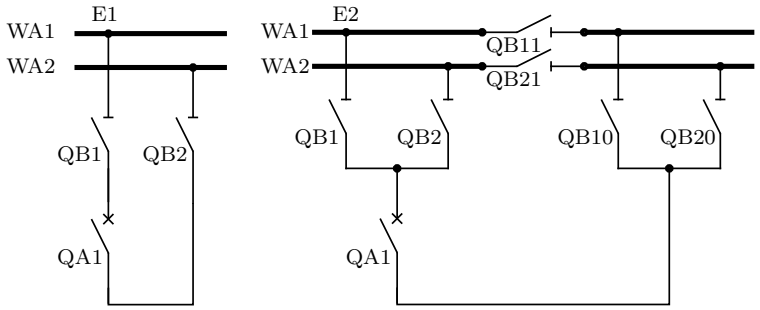


Figure 6.6: Double busbar configuration - feeder E2 with an extra switch E2-QB6 and feeder E3 with an extra switch E3-QB5

Switches in Coupling Bay

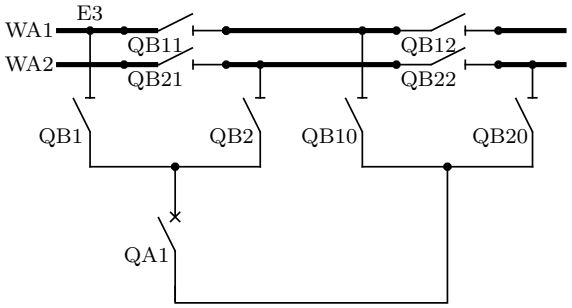
Previous sections describe criteria to check the validity of feeder bays. One criterion is the number of switches which can be used to check if all needed switches for the configuration are installed. Further criteria can be used to verify the configuration of switches. But in coupling bays the number of switches does not provide any information to check the validity. For example to connect two busbar sections only one disconnecter, i.e. a sectionalizer is needed. Coupling of two busbars as presented in figure 6.7(a) requires three switches. [2, p. 498f.] presents different couplings for double and triple busbar configurations. The number of switches needed for these configurations varies from five to fourteen switches for double busbar configuration. For triple busbar configuration five to sixteen switches can be used for coupling. The different number of switches is needed to provide the flexibility needed to couple the wanted sections and busbars. Figure

6.7(b) shows a coupling with seven switches and figure 6.7(c) a configuration with nine switches, as they are presented in [2, p. 498].



(a) Example 1: double busbar

(b) Example 2: sectionalized double busbar [2]



(c) Example 3: sectionalized double busbar [2]

Figure 6.7: Examples of coupling bays for double busbar configurations

Testing a coupling bay can be done by:

- Checking the number of switches from one busbar section to another. Allowed is a maximum number of three switches to allow using the rules defined in section 5.1 for the length of the parallel path. The number of three switches corresponds to a combination of a disconnector a circuit breaker and a disconnector to couple different busbar sections.

- Checking if the bay has no cycles to ensure that a connection of different busbar sections has no parallel path. The algorithm to test that is described in section 6.3.

6.3 Test on Cycles

Section 6.1 presents a solution to check reachability. Section 6.2 shows how to check the number of switches in a bay to verify the substation type. But moreover a test is needed to check as well if the proposed search algorithms are suitable to deliver correct decisions. The presented interlocking rules in section 5.1 depend on the potential double or on parallel paths. The potential double can be checked with the modified BFS. Finding all parallel paths is a problem for BFS and DFS which is discussed in section 3.2. The problem is solved with adapting the length of switch and modifying search strategies in section 4.4. The algorithms work for the presented substation configurations because these configurations do not provide any loops when they are directly linked to two busbars. The limits of the modified search strategies are discussed here. The interlocking decisions depend on the potential double and the parallel paths. Finding the potential double is no problem but finding all relevant parallel paths with the correct length is a problem. Following types of parallel paths for interlocking decisions can be identified:

- A parallel path in a feeder bay. Here is only one path possible - e.g. shunt disconnector. This parallel path will always be detected with BFS or DFS even without any adaptations because if at least one connection exists between the two nodes then BFS and DFS find at least this one connection.

- A parallel path that passes at least three busbars is always found with modified BFS and DFS, because of starting and ending at the busbars. The information of such a path is necessary to prevent closing a ring and lose selectivity in a normal busbar configuration. Figure 6.8 shows an example of a parallel path (dashed line) including three busbars[19]. Of course more parallel paths will exist in feeders but if only one is detected switch E1-QA1 is not allowed to be closed, to keep selectivity.

- A busbar coupling. Opening a coupling in normal busbar configurations requires that all parallel paths between the two directly linked busbars are discovered. Figure 6.9 shows a triple busbar configuration which shows the paths that are needed to be discovered for interlocking decisions. The proposed modified DFS starts and ends therefore at the busbars to find the requested parallel paths. Furthermore

[19] Example is reduced to couplings only to demonstrate what is meant by a path including three busbars

it is necessary that there are no cycles directly between the two busbars, so that DFS is able to find all existing parallel paths.

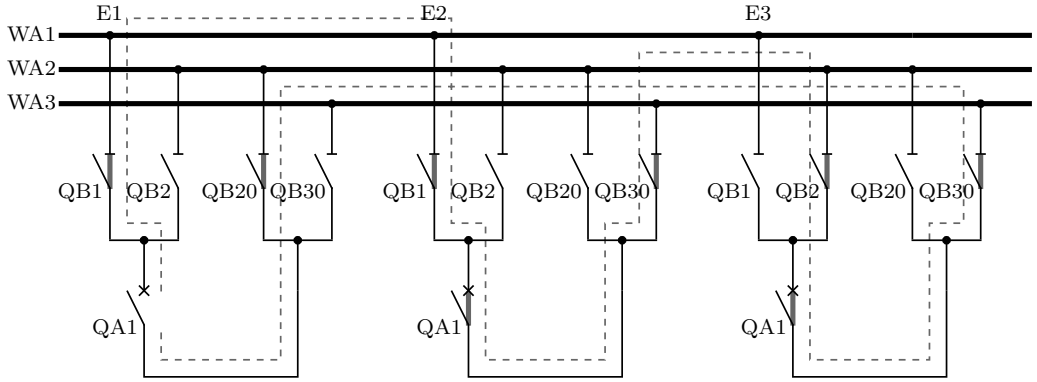


Figure 6.8: Example 1: Parallel path (dashed line) including three busbars for switch E1-QA1

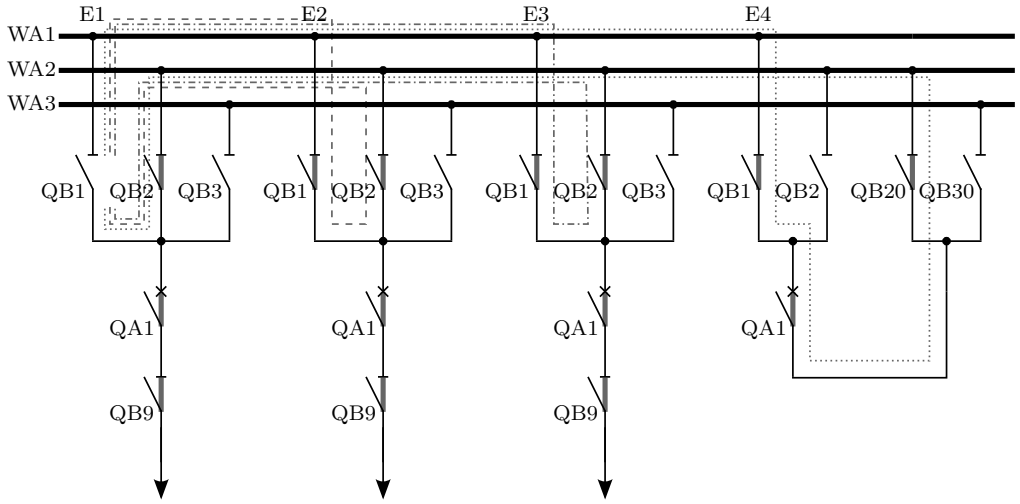


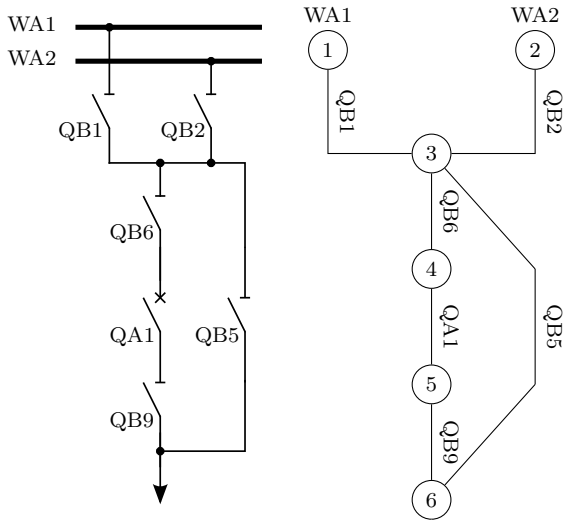
Figure 6.9: Example 2: Three parallel paths (dashed, dash dotted, dotted line) between the two directly linked busbars for switch E1-QB1

To test if a graph is free of cycles DFS can be used [13, p. 173]. DFS is then used to check if an undiscovered edge leads to an already discovered node. If so then cycles exist in the graph. So DFS can be used to start at each busbar sections to check if adjacent switches produce any cycles until DFS reaches other busbar sections. Therefore the following conditions have to be considered for all busbar sections in a substation:

- Use a busbar section as starting node for DFS
- Do not add a new node that is any other busbar section to the stack - to not continue searching at that point.
- Do not add a new node that is an earth node to the stack - to prevent any problems as described in section 6.1
- Exclude following switches:
  - shunt disconnectors because they produce loops in bays but they do not influence DFS when searching parallel paths for couplings of busbars.
  - bypass switches and
  - cross-tie switches as well because a bypass or cross-tie switch might lead back to the busbar section where DFS started. Cycles produced by these switches can be handled as well with the described interlocking rules in section 5.1 because they lead back to the busbar.

Figure 6.10 shows a bay with a shunt disconnector and a graph of such a bay. The following example for the shunt disconnector demonstrates that this loop does not influence finding the parallel path between busbars. Therefore this switch can be ignored when checking the topology with DFS. DFS starts at node 1:

- And edge E1-QB1 leads to node 3,
- Then leads edge E1-QB6 to node 4, with edge E1-QA1 to node 5 and edge E1-QB9 to node 6.
- Edge E1-QB5 is identified as a loop edge because the edge leads back to the node 3.
- Continuing search at the node with undiscovered edges leads to node 3 and with edge QB2 node 2 is discovered and the second busbar is found. The path of the loop with switches QA6, QA1, QB9 and QB5 is not part of the path between the busbars WA1 and WA2 with switches QB1 and QB2.



(a) Shunt disconnector bay

(b) Diagram of graph representing the shunt disconnector bay

Figure 6.10: Shunt disconnector bay

Topology Causing Cycles

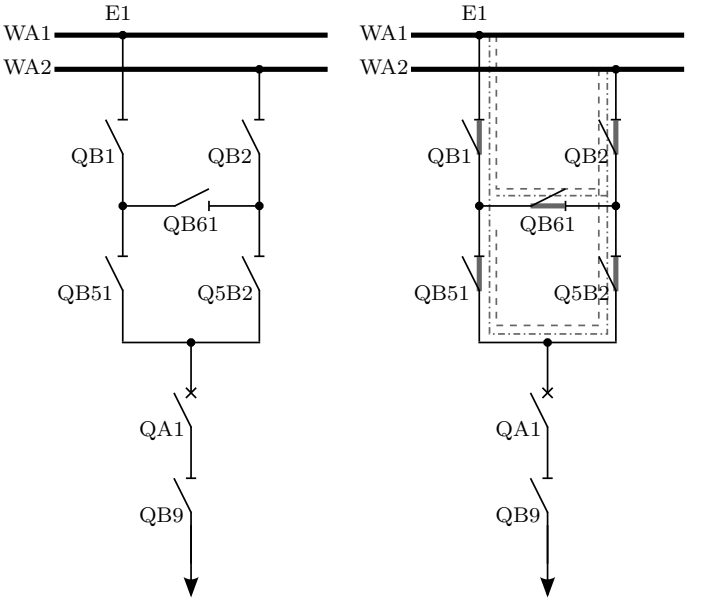
An example of an unusual bay configuration is given in figure 6.11(a) and would not be used in real substations. This configuration is not real but presented to demonstrate the problems that come up. Switches E1-QB51, E1-QB52 and E1-QB61 are not needed and would therefore not be installed in a bay. Figure 6.11(b) presents possible paths found with DFS. When switches E1-QB1, E1-QB2, E1-QB51, E1-QB52 and E1-QB61 are closed two different paths can be detected.

- Path 1 - dashed line: Starting at busbar WA1 leads to switch E1-QB1, to E1-QB61 and with E1-QB2 to busbar WA2, reaching the busbar with a length of 3 switches. Further on with switches E1-QB52 and E1-QB51 a loop is detected.
- Path 2 - dash dotted line: Staring at busbar WA2 leads to switch E1-QB1, to E1-QB51, to E1-QB52 and with E1-QB2 to busbar WA2, reaching the busbar with a length of 4 switches. Switch E1-QB61 closes the loop.

In this case DFS will not find both paths because of the loop. Besides that it can not be predicted which path will be found. Discovering the edges depends on the order the edges are placed in the adjacency list. If edge E1-QB51 is placed before E1-QB61 in the

list, then the path with length four is detected. The other way round would result in a path with the length of three. For that reason starting DFS from busbar WA2 will not deliver any other results. Therefore these configurations have to be identified and the length of parallel paths can not be used.

But even for that configuration safety relevant interlocking is possible. Operational rules that are formulated independent on the topology can be applied as well. Any rules that are based on the length of the parallel paths can not be applied because the length can not be evaluated for sure.



(a) Unusual bay configuration for double busbar

(b) Possible parallel paths from one busbar to the other one marked with dashed and dash dotted line

Figure 6.11: Unusual bay configuration

Another configuration that does not work for topology dependent operational interlocking, is a bay with a shunt disconnector which is connected to an auxiliary busbar. The shunt disconnector allows to bypass the circuit breaker, therefore an auxiliary busbar is not needed for maintenance of the circuit breaker so this configuration will normally not be used. The loop caused by the shunt disconnector between main busbar and auxiliary busbar does not guarantee to find the correct length of parallel paths. Figure 6.12 shows such a configuration. One path is marked with a dash dotted line passing switches E1-

QB1, E1-QB6, E1-QA1, E1-QB9 and E1-QB7 with a length of five from busbar WA1 to WA7. The second path marked with a dashed line passes the switches E1-QB1, E1-QB5 and E1-QB7 with a length of three. As described in the previous example, discovering the edges depends on the order the edges are stored in the adjacency list. Therefore if switches are closed as presented in the figure, it is not possible to find a unique parallel path, in this configuration. So topology dependent operational interlocking which uses the length of parallel paths is not working for this configuration as well.

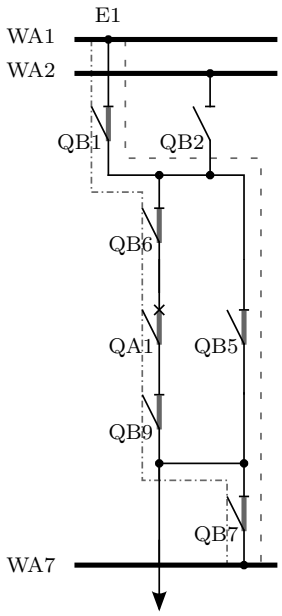


Figure 6.12: Example configuration with shunt disconnector and auxiliary busbar

Summing up the introduced validity check algorithms in this chapter, it can be conducted that

Reachability is absolutely needed for topology based interlocking.

- If reachability is not given then the configuration is not valid and it is obvious that equipment is missing in the configuration.
- Therefore reachability proven with transitive closure is absolutely needed for topology based interlocking.

Check Number of Switches is needed to compare the bays in the substation to identify the configuration and to identify additional or missing switches.

- If all bays identify the same type and the number of switches is equal for all bays then a valid substation configuration is given. So safety relevant and operational interlocking can be used for the substation configuration.
- If a valid substation configuration with missing switches or additional switches is identified but the length length between busbars is not influenced, a warning is generated to make sure that the missing switches are left out intentionally but safety relevant and operational interlocking is possible.
- Additional switches for a valid substation configuration that influence the length between busbars require adaptations for the length of the additional switches to not change length of parallel paths used for operational interlocking. The adaptation requires for the identification of parallel path with DFS because BFS is no longer able to identify the shortest parallel path.
- For any configuration that can not be identified safety relevant and topology independent operational interlocking can be provided.

The **Test on Cycles** is needed to prove that the proposed algorithms are suitable to find all relevant parallel paths for operational interlocking.

- If the test on cycles does not identify any cycles then it is proven that the proposed algorithms are suitable to find all relevant parallel paths for operational interlocking.
- If cycles are found with the proposed test algorithm, then the length of parallel paths can not be clearly identified. In this case safety relevant and topology independent operational conditions can be used only for topology based interlocking.

7 Conclusion

Topology based interlocking is easy to configure for safe and flexible operation in substations. Compared to Boolean equations the amount of engineering amount is reduced. Moreover, interlocking with Boolean equations gets very complex for large substations and is prone to errors. Extending a substation with new bays might require to edit all Boolean inter bay interlocking equations, which is nearly the same effort as a complete redesign of the interlocking conditions. Compared to Boolean equations topology based interlocking provides following advantages:

- Topology based interlocking has low engineering demand.
- Defined rules can be applied to any suitable substation configuration.
- The reason for the interlocking signal can be delivered to the operator so that it is possible to distinguish between safety relevant and operational reasons. This allows to overrule operational interlock signals in urgent situations but ensures safety relevant interlocking.

The solutions presented in this thesis provide topology based interlocking for safety relevant and operational interlocking conditions. Operational interlocking is solved in presented literature with complicated solutions. Search strategies are used to return a list of passed switches which has then to be evaluated with specified criteria. But not all operational interlocking conditions can be covered by those criteria, for example the switching sequence, coupling of network groups, rules for 1 ½-breaker method substations. The previously proposed search strategies as depth-first search are not suitable to find all relevant parallel paths, as discussed in chapter 3 or they are inefficient for

searching all relevant paths because nodes and edges have to be searched multiple times.

This thesis proposes to reduce parallel paths to a single criterion - the length of parallel paths. Therefore the length of switches is proposed to ensure that longitudinal coupling does not influence the length and longitudinal coupled busbars appear as a single node for search strategies. This solution allows to use the length of a parallel path as unique criterion for interlocking decisions. As presented in chapter 5 different configurations provide different lengths of parallel paths to generate correct interlock or enable signals for each configuration. In this thesis adaptations for depth-first search are proposed to continue using the simple search strategies to find all relevant parallel paths in a substation without searching edges and nodes multiple times. Adaptations are proposed for breadth-first search to ensure the shortest parallel path is found for different switch lengths.

The additional property of network groups is introduced for nodes. Network groups allow to group feeders and can be used to prevent connections between feeders due to operational reasons.

To provide redundancy it is proposed to use bay controllers for topology based interlocking so that it is possible to generate interlocking decisions decentralised in each bay. Therefore solutions are presented to reduce the topology for each bay controller to increase the performance of the search strategies. For the configuration of bay controllers it is proposed to use the standard IEC 61850 which includes a standardised description of substations. This standard is suitable with presented solutions to automatically identify the topology of a substation, the substation type and switch types for topology based interlocking. Furthermore, it is proposed to use the standard to automatically set up communication for bay controllers to exchange relevant switch positions.

Chapter 6 presents solutions to automatically check the validity of the substation configuration. With proposed algorithms it is possible to check if the reachability is given or errors exist in the topology. Also it is possible to check if the configuration is valid for the proposed search strategies. If so, safety relevant and operational interlocking conditions can be applied. If not, topology based interlocking can only be used with safety relevant and topology independent operational interlocking conditions.

Therefore it is possible to use topology based interlocking for load-center substations as well, as presented in section 5.1.8.

For future applications standard IEC 61850 provides (in combination with the topology) additional possibilities. Taking into account that data from voltage and current transformers is supplied with the standard as well, it is possible to:

- Check if the correct assignment of switches and voltage transformers is possible by connecting these switches to a test voltage.
- Evaluate load flow situations in the control center using the current topology. With a grid model it is then possible to derive suggestions to calculate reliability indices of the current switch configuration. As a consequence it would be possible to suggest reconfigurations to reduce the value of lost load in case of failure.
- Continuously test the values provided by current and voltage transformers. With current switch position it is possible to continuously check if voltage and the sum of current is correct and so no fault is given in the measuring devices.
- Check if a line, transformer or generator is energized or de-energized with current and voltage transformers to update node potentials in the substation. Alternatively it is possible to check adjacent voltage transformers to make sure that a node is de-energized to connect equipment to earth potential.

8

Appendix

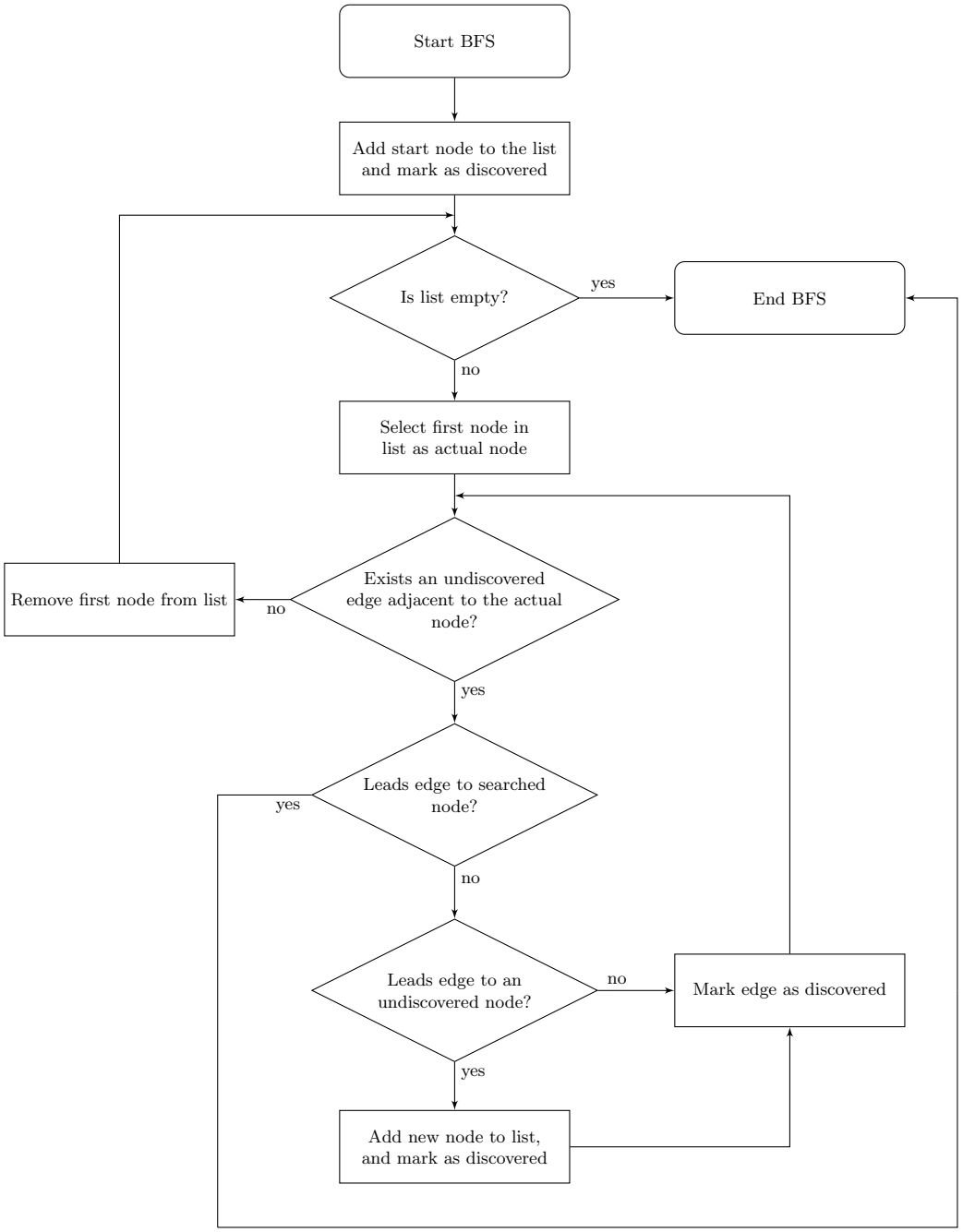


Figure 8.1: Flowchart of breadth-first search

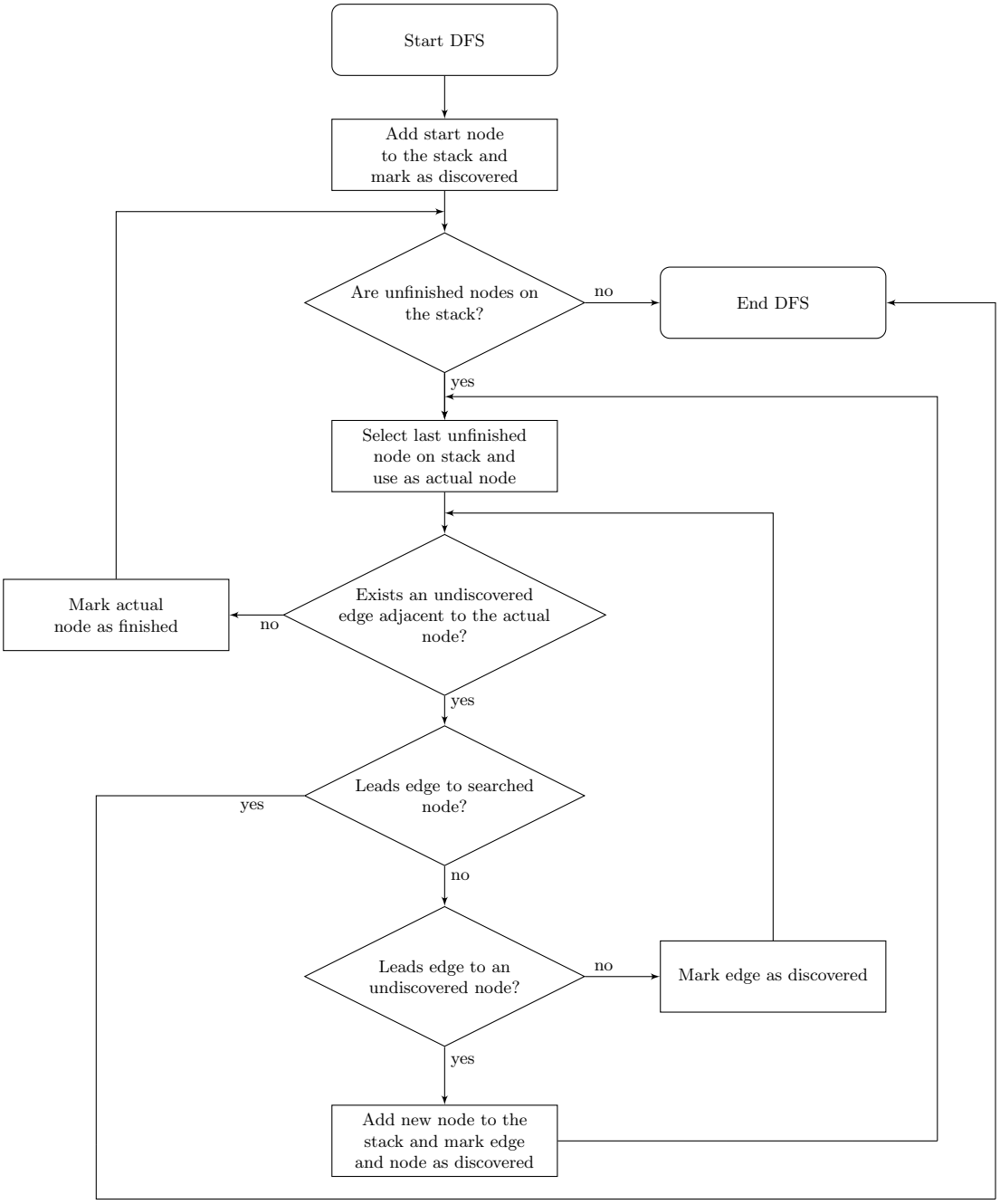


Figure 8.2: Flowchart of depth-first search

Abbreviations

BFS	breadth-first search
CBR-C	circuit breaker in a coupling bay
CBR-F	circuit breaker in a feeder bay
CBR-T	circuit breaker in a transformer bay
CID	Configured IED Description
DFS	depth-first search
DIS-C	disconnector in a coupling bay not fitting in any other specification
DIS-C-BB	disconnector in a coupling bay adjacent to a busbar
DIS-C-S	disconnector in a coupling bay used as sectionalizer
DIS-E-BB	earthing switch adjacent to a busbar
DIS-E-C	earthing switch in a coupling bay
DIS-E-F	earthing switch in a feeder bay
DIS-E-FG	earthing switch in a feeder bay adjacent to a DIS-F-BB
DIS-E-L	earthing switch adjacent to a line, load or source
DIS-E-T	earthing switch in a transformer bay

DIS-F	disconnector in a feeder bay not fitting in any other specification
DIS-F-BB	disconnector in a feeder bay adjacent to a busbar
DIS-F-CT	disconnector in a feeder bay used as cross-tie disconnector
DIS-F-SD	disconnector in a feeder bay used as shunt disconnector
DIS-F-Y	disconnector in a feeder bay used as bypass switch
DIS-T	disconnector in a transformer bay
DIS-T-BB	disconnector in a transformer bay adjacent to a busbar
GOOSE	Generic Object Oriented Substation Events
GSE	Generic Substation Events
GUI	Graphical User Interface
ICD	IED Capability Description
IED	Intelligent Electronic Device
SCD	Substation Configuration Description
SCL	Substation Configuration Language
SSD	System Specification Description
XML	eXtensibel Markup Language

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