Diplomarbeit

Variable speed generator concepts for hydro power plants

ausgeführt am

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unter der Leitung von

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Kurzfassung

Erneuerbare Energiequellen wie Sonne, Wind und Wasser spielen im 21. Jahrhundert eine immer wichtigere Rolle für die Stromerzeugung. Um die Netzstabilität bei steigendem Einsatz von zentralen und dezentralen Anlagen der Energieerzeugung gewährleisten zu können, müssen jene in der Lage sein einen aktiven Beitrag zu Stabilität zu liefern.

Abhilfe können Pumpspeicherkraftwerke mit drehzahlvariablen Konzepten schaffen. Maschinensätze mit variablen Drehzahlen sind in der Lage, das Betriebsverhalten zu optimieren, mit einem verbesserten Wirkungsgrad zu arbeiten und somit die erzeugte Energie zu erhöhen. Drehzahlveränderbare Konzepte in Pumpspeicherkraftwerken können somit den gestiegenen Anforderungen der Netze hinsichtlich Flexibilität, Speicherkapazität und Wirkungsgrad gerecht werden.

Weltweit wurden bereits mehr als 25 Pumpspeicherkraftwerke mit drehzahlvariablen Maschinensätzen, vor allem im asiatischen Raum, gebaut. Zwischenzeitlich hat aber auch Europa den Trend zu drehzahlvariablen Konzepten erkannt. Das derzeit größte drehzahlvariable Pumpspeicherkraftwerk Goldisthal vollendet im Jahr 2004 mit einer Gesamtleistung von 1120 MVA besitzt 520 MVA mit fester und 600 MVA mit variabler Drehzahl. Anderseits, wurde 2013 im Kraftwerk Grimsel 2 im Zuge des Refurbishments der vorhandenen Einheiten eine 100 MVA Einheit auf drehzahlvariablen Betrieb umgerüstet.

Insbesondere sind bei Mikro- (unter 100 kVA je Einheit) bis kleinen (bis 10 MVA je Einheit) Wasserkraftanlagen vielfach permanentmagneterregte Synchronmaschinen gespeist über einen Umrichter mit variabler Frequenz im Einsatz. Bei den höheren Leistungen sind dabei auch doppelt gespeiste Asynchronmaschinen in Verwendung. Im Bereich größer als 10 MVA je Einheit sind aus derzeitiger Sicht jedoch doppelt gespeiste Asynchronmaschinen die meist eingesetzte Ausführung. Zukünftig werden durch die Weiterentwicklung der Umrichtertechnologie in diesem Leistungsbereich auch vermehrt Synchronmaschinen verwendet.

Im Sinne dieser Einteilung nach der Leistung einer einzelnen Einheit wird auch das Zusammenwirken mit den unterschiedlichen Typen von Turbinen und Pumpen erläutert. Dabei werden im Vergleich zwischen den Konzepten mit einerseits fester und anderseits variabler Drehzahl die vielfältigen Vorteile der letztgenannten Ausführungen deutlich. Demzufolge wird abschließend festgestellt, dass Wasserkraftanlagen mit variabler Drehzahl den heutigen Anforderungen an die elektrische Energieerzeugung hervorragend gerecht werden.

Abstract

Renewable energy sources, such as solar-, wind- and water power, play an more and more important role for electric power generation in the 21th century. In order to provide grid stability for increasing utilization of distributed power generation, these power plants must deliver an active contribution to grid stability.

Pumped storage power plants with variable speed units are there to help. Variable speed units optimise operation behaviour, can operate at improved efficiency and increase the generation sufficiently. Therefore, variable speed units at pumped storage hydro power plants are able to meet the higher grid requirements towards flexibility, storage capacity and efficiency.

Worldwide, more than 25 variable speed pumped storage power plants have already been built, especially in Asia as well as Europe has found its way to realise variable speed units. The pumped storage power plant Goldisthal is presently the largest pumped storage power plant with a total output of 1120 MVA, splitted in 520 MVA with fixed speed - and 600 MVA with variable speed operation. Contrariwise, Grimsel 2 power plant was expanded while a refurbishment at one unit with the world's largest direct converter for a storage power plant with 100 MVA in 2013.

Particularly for micro (lower 100 kVA per unit) to small (until 10 MVA per unit) sized hydro units with an electric or permanent magnet excited synchronous generator fed with variable frequency by a direct converter will be implemented. At higher power doubly fed asynchronous machines are used, too. At a unit power larger than 10 MVA nowadays doubly fed asynchronous machines are by far the most realised concepts. In the future, the developments of the converter technology and on-going decrease of specific costs, synchronous speed concepts will be realised more often.

After an overview of turbines and pumps, their modes of operation are explained and the comparison of fixed and variable speed operation shall demonstrate the wide range of advantages of variable speed operation. Because of these advantages hydro power plants with variable speed operation capability can significantly contribute to meet the requirements of the electric grid system operators.

Content

1. Introduction

Renewable energy sources, like solar, wind and water, play an increasingly important role for electric power generation in the 21th century. The global warming and CO_2 emissions avoiding is more important than ever and this awareness has helped to increase electric energy generation from renewable resources.

In the past, wind farms used to be small and they were simply disconnected in case of a grid failure. Nowadays, their number has increased rapidly. As the penetration of wind power in electrical power systems increases, disconnection of wind farms during faults is not desirable any longer as this may lead to instability of power systems due to the loss of large generation capacities.[1] Photovoltaic instead was common for its self-usage and the efficiency of the panels has increased throughout the time and became more and more suitable for the electric power generation.[2]

Therefore, transmission systems have to face new challenges as the design of most transmission and distribution networks. The volatile energy sources, like wind and solar, lead to more unpredictable power generation, because of impact of environmental conditions such as the amount of sunshine and wind velocity. During day and night times, holidays and seasons the demands of energy vary a lot and with the turnover to electric mobility, new challenges for the grids will result. The high amount of volatile renewable energy sources in the grids has dramatically changed the requirements for power plants.

A quick response to actual electric power demand with a high efficiency is needed. Hence to that, hydro power, especially pumped storage could be a solution to compensate the grid fluctuations.

Conventional pumped storage power plants are usually operated at fixed speed, which generate grid frequency with a defined number of poles. At fixed speed operation, when the hydraulic parameters are changing, the turbine's efficiency is not at its best point. Therefore, optimised equipment for a wide operating range is needed. Variable speed units at pumped storage hydro power plants are able to meet the increasing requirements of the transmission system operators with regard to flexibility, storage capacity and efficiency.

[1] F. Cazzato @all,Connection of Distributed Generation to Enel's Network in the Transition Period from Passive Networks to Smartgrids 2009.

[2] https://pesserportal.de/photovoltaik/pm

The purpose of this thesis is on one hand a look at the different machine concepts and on the other hand to discuss advantages and drawbacks of both turbines and pumps to be used with variable speed operation.

Starting from a short overview of electric power generation, hydro power plants and their components as well as the concepts of variable speed units are presented. Thereby, the electric machines and the related power electronics as well as the various types of turbines and pumps for the variable speed operation and their aspects at different operation modes are discussed.

A comparison of the different variable speed concepts shows their differences, applicability and economic situations. Afterwards, an overview of already built pumped storage power plants using variable speed and their designs are presented in detail. The final conclusion of this work will reveal which concept is common nowadays and what will be accomplished in the future.

2. Electric power generation

Electric power generation is the process of converting various energy sources to electric energy. Worldwide the electric energy demand is increasing rapidly bringing the overall transmission system to its limits in influencing system behaviour and stability. In electric power generation, supply and demand are not always matching up at any given time. The power plants would prefer to generate always the same amount of electricity at day and at night times. It is obvious that there is not always the same amount for energy. Finally the turn-over to electric mobility will result in novel challenges and strategies for the electric power generation as well as distribution.

Nowadays the focus of energy generation is more than ever at renewable energy sources, such as solar and wind and at least water. The first two mentioned sources are depending on the weather conditions and are requiring electricity storage due to that. The surplus electricity, which is obtained from the renewable energy sources need to be stored so that it can be feed back into the grid when needed. Otherwise power outages and consequently economic damages may be the consequences. To balance the worldwide rising demand, storing is the only solution to overcome the discrepancy of actual generation and consumption.

Storage of electric energy is not as simple as storage of water or oil; it has to be converted temporarily into another form of energy. This transformation leads to higher costs and certain technologies are still too inefficient to be used for it. Therefore, a good way to store energy is by means of hydroelectric storage power plants, and here especially pumped storage power plants, which have the opportunity to generate energy as well as consume energy when it is needed.[3]

2.1. Electric power grids

A power grid is a network of power lines and associated equipment used to transmit and distribute electricity over a geographic area from parallel operating generating units, the suppliers, to distributed consumers.[4] The dimensions as well as the number of parallel operating generators and connected costumers define the complexity of the grid. It consists of three main components:[5]

- GENERATION which are power plants generating electric energy from primary resources.

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[3] https://www.planete-energies.com/en/medias/close/storing-electricity-key-managing-energy

[4] https://www.collinsdictionary.com/dictionary/english/power-grid

[5] http://www.science.smith.edu/~jcardell/Courses/EGR220/ElecPwr_HSW.html

We differentiate between two types of generation – the centralized one and the decentralized one. Centralized generation refers to large-scale generation far from the consumers. This includes coal, nuclear, natural gas, hydro, geothermal, wind farms and large solar arrays. The grid connects centralized power to consumers. Decentralized generation occurs close to consumption, for example rooftop solar plants.

- TRANSMISSION and DISTRIBUTION: Transmission includes transformers, substations and power lines that transport electricity from where it is generated to the points of consumption. When electricity is at high voltages, transmission losses are minimized over long distances and resistive transmission lines. Therefore, at the point of generation, substations contain transformers that step-up the voltage of electricity so that it can be transmitted very efficiently. Transmission is achieved via power lines and can occur either overhead or underground. When it arrives at points of consumption, another substation is found to step-down the voltage for end-use consumption.
- CONSUMPTION: There are various types of consumers; namely industrial, commercial and residential consumers. Each of these consumers has different needs but in general electricity delivers important energy services like light and power for appliances.

Electrical grids vary in size from covering a single building through national grids, which cover whole countries, to transnational grids, which cross continents (Figure 2-1). There are various possibilities to define grids:[6]

1. Definition by its purpose:
    - Transportation grids: for the transportation of the energy over long distances
    - Distribution grids: for the distribution of the energy to the individual customers

[6] http://electrical-engineering-portal.com/primary-distribution-voltage-levels

2. Definition by classification of the operation voltage, voltage type or system type:

<u>Operation voltage:</u>

- High or ultra-high voltage girds (transportation grids)
- Middle or low voltage grids (distribution grids)

<u>Voltage type:</u>

- AC grids
- DC grids

<u>System type</u>:

- Three-phase grids
- Single-phase grids

The governing body of all European transmission system operators (TSO) is named ENTSO-E (European net transmission system operators-electric) see Figure 2-2.

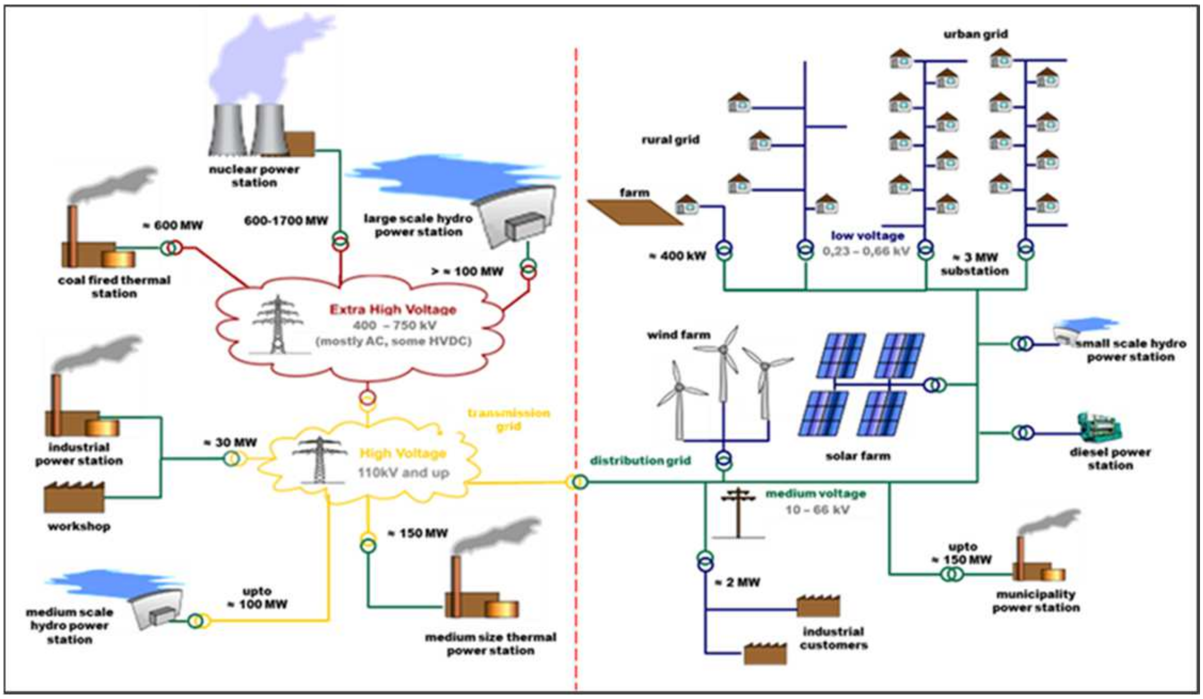


Figure 2-1 Configuration of a meshed electric grid[7]

[7] https://www.studentenergy.org/topics/electrical-grid

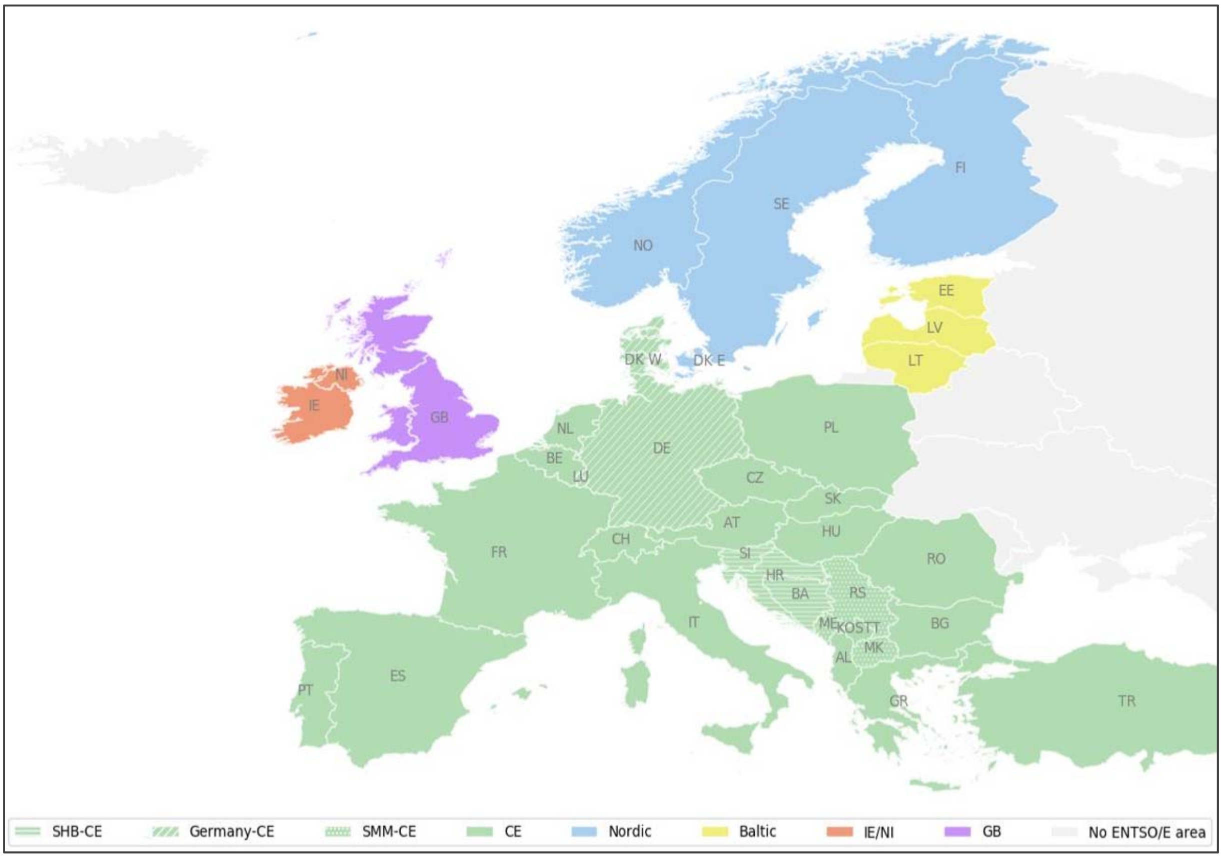


Figure 2-2 ENTSO-E map of European synchronous areas and load frequency control (LFC) blocks[8]

As electric energy generation has to be balanced with the actual consumption at any moment, regulation of generation is very important in every electricity network to ensure stability and reliability of the energy supply.

For a trouble free grid operation the following criteria must be fulfilled:

- Constant frequency (within a small tolerance band):
  Since the frequency is identical everywhere in the grid, it can be controlled by a few power stations only (centralised).
  Frequency control = active power control by means of the turbine governors.

- Adjustable voltage level (within certain limits):
  Due to the distributed and different impedances in the grid the voltage control is a pure decentralised task.
  Voltage control = reactive power control by means of the generator excitation and/or adaptable transformer ratio.

[8] Cf. European low-carbon challenge and the electricity network-Entso-e

For keeping the power system frequency within secure limits, the responsible transmission system operators (TSO) shall maintain the balance between load and generation on a short-term basis. Grid instability can lead to malfunctions all over the grid, as not only power plants but also the grid customers are affected. Because of this it is very important to stay inside the grid limits. A deficiency of energy can lead to a frequency drop or a power loss in the system. Although the energy consumption varies significantly over the day, other influencing factors or big regional events as well as other circumstances can lead to a non-predictable change of energy generation or consumption see Figure 2-3. With the increase of rather volatile renewable energy sources new grid codes have been established recently. All TSO have to ensure that the energy producers keep the variations of their supply within the limits and that consumption as well as grid failures like short circuits will be compensated. While the fossil energy sources get more and more limited, and volatile renewable energy sources such as wind and solar energy cannot compensate the energy peak loads in a sustainable way, reliable and predictable hydro power can be used to maintain stability. Hydro plants with variable speed technology are able to support grid stability more effectively as those with fixed speed arrangements.

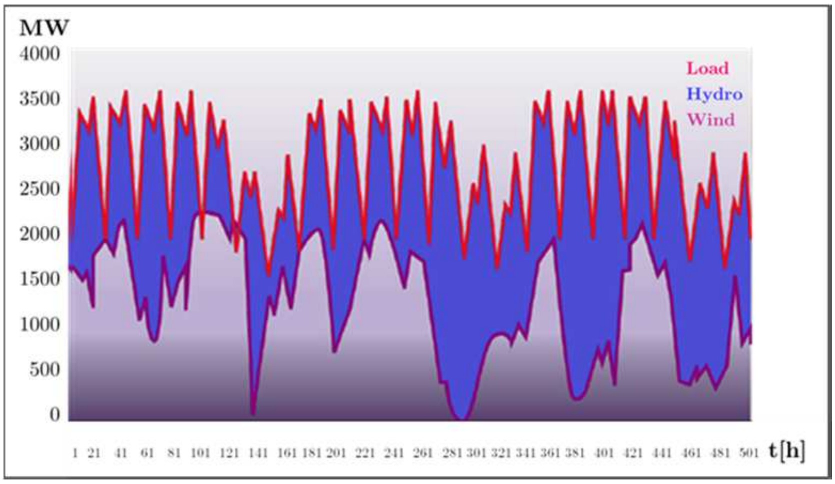


Figure 2-3 3-week cycle of generation of wind and hydro and consumer load[9]

To demonstrate the low generation predictability of volatile renewable energy sources just one example from the wind industry in western Denmark (Figure 2-4):
Today Denmark has the highest wind penetration in the world. If the wind forecast ranges from gentle breeze to fresh breeze the power output can vary between 200 to 1600 MW. Depending on where the production level is on the turbine generation curve, a deviation in the wind forecast of ± 1 m/s can result in the change of power generation as of ± 320 MW.

[9] IEA- World Energy Outlook 2010; IEA-Projected costs of generating electricity 2010

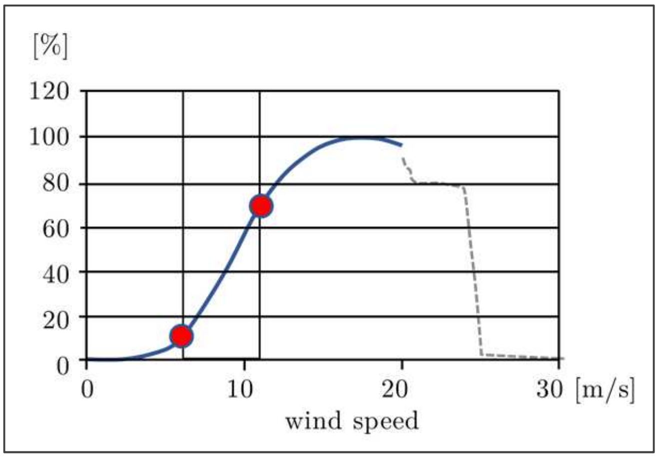


Figure 2-4 Aggregated wind production curve for western Denmark

Figure 2-5 shows the big change in consumption effected by a simple soccer match. The diagram shows the generation / pumping reaction of the Schluchsee scheme during the world championship soccer final between Germany and Argentina on July 8th, 1990. It demonstrates the extreme high volatility of the energy consumption in the south-west part of Germany.

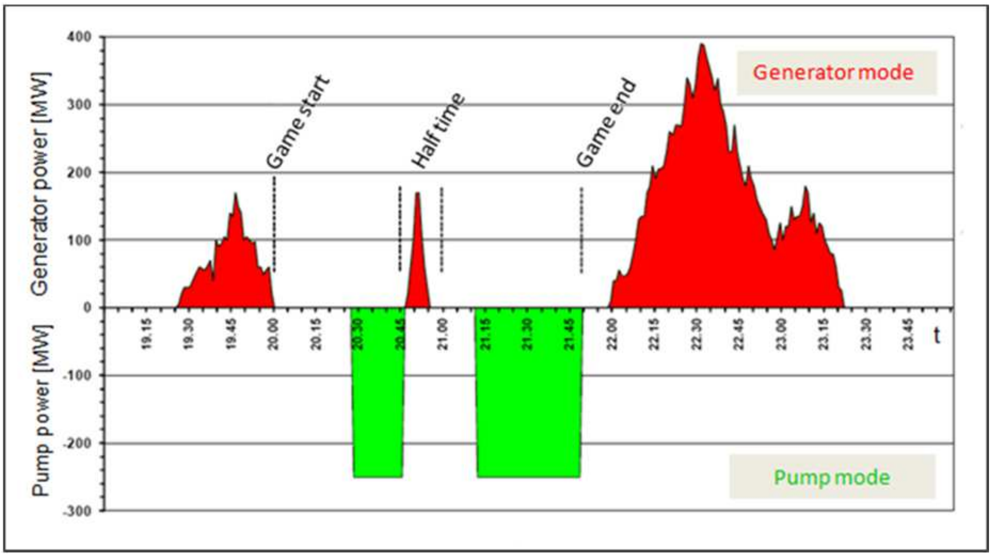


Figure 2-5 Generation of Schluchsee scheme during a championship soccer final[10]

[10] Schluchseewerke AG-11/1990

2.2. Energy mix and power generation mix

The term “energy mix” refers to the combination of the various primary energy sources used to meet energy needs in a given geographic region and/or from which secondary energy for direct use - usually electricity - is produced. It includes fossil fuels (oil, natural gas and coal), nuclear energy, non-renewable waste and the many sources of renewable energy (wood, bio-fuel, hydro, wind, solar, geothermal, heat from heat pumps, renewable waste and biogas). These energy sources are used, for example, for generating electric power, providing fuel for transportation and heating and cooling residential and industrial buildings.[11]

For each region or country, the composition of the energy mix depends on:

- The availability of usable resources domestically or the possibility to import them
- The extent and type of energy needs to be met
- Policy choices determined by historical, economic, social, demographic, environmental and geopolitical factors

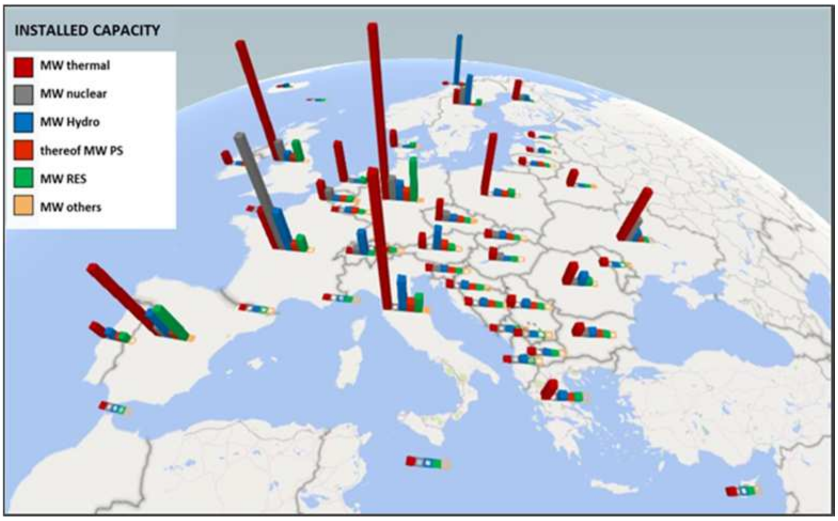


Figure 2-6 Installed power plant capacity[12]

The term energy mix should not be confused with the term power generation mix, which is the percentage of different energy sources (fossil fuels, nuclear, hydro and other renewable energies) used to generate electricity. For this reason, it does not take into account issues surrounding energy use in transportation and large sectors of industry and housing.

The new energy area sets their focus on renewable energy such like photovoltaic, wind generation, biomass and hydro power. In the year 2018 more than 14,5 % of the

[11] https://www.encyclopedia.com/energy+mix/

[12] https://ec.europa.eu/eurostat/web/energy/data/shares

energy needed worldwide was generated by renewable energy sources (incl. hydro but without pumped storage power plants). 14,4 % of the electric energy needed in Europe and 16,7 % of the whole world is produced by hydro-electric power plants (Figure 2-7). (BIP stats 2019)[13]

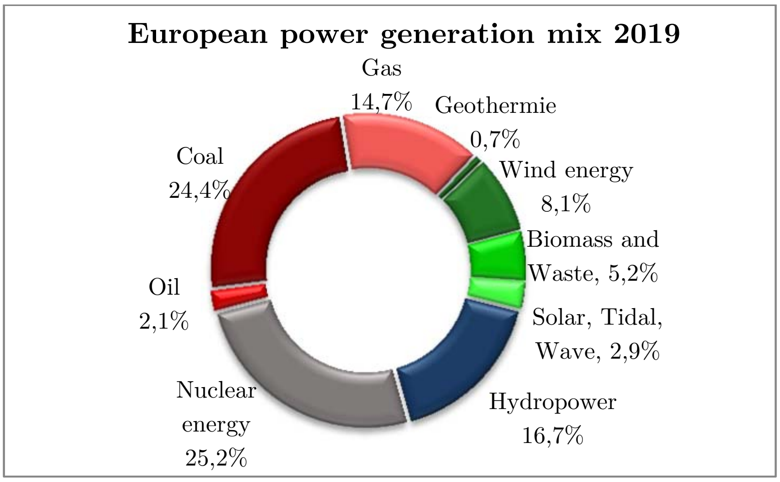


Figure 2-7 Energy power generation in Europe 2019[14]

With a closer look at the European continent it has to be said that the European Community (EC) has developed an energy strategy in 2010 and defined various goals for 2020. Further road maps looking ahead until 2050 are published. The EC stated that over the next ten years, energy investments in the order of € 10^9 are needed, both to diversify existing resources and replace equipment as well as to cater for challenging and changing energy requirements. Structural changes in energy supply, partly resulting from changes in indigenous production will be necessary. The integration of indigenous renewable generation on the power system is considered a means to achieving energy security, environmental sustainability and economic competitiveness simultaneously.
Integrating renewable energy generation on the power system can impact the operation of the system in a number of important ways.

First, a central feature of renewable generation is that it is variable in nature: the wind blows, the sun shines, and the tides ebb and flow. The management of this variability can only be achieved through a combination of improved forecasting, increased control capability of conventional and renewable generation and new operational strategies.

Secondly renewable generation uses different technologies such as fixed speed as well as variable speed concepts. The level of penetration of these technologies can materially alter the characteristics of the power system creating challenges not only

[13] http://www.bp.com/statisticalreview-2019/06

[14] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:0639:FIN:En:PDF..

in balancing the system in real time but also in long term adequacy, system transient stability, network steady state voltage control and disturbance response. Managing these situations requires a range of system services (on the generation and demand sides of the market) to be available in multiple timeframes.[15]

2.3. Energy generation

The energy consumption of a day differs in every country and every day. Neither the energy consumption nor the respective renewable energy source like wind and solar energy can be forecasted exactly. Figure 2-8 shows the electricity production from wind (green) and solar energy (yellow) in Germany within September 2011.

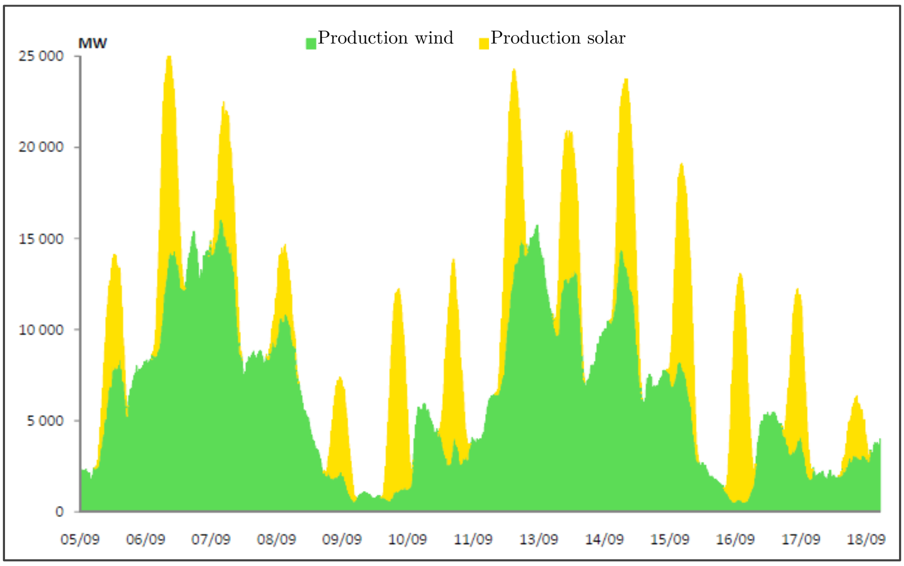


Figure 2-8 Electricity production from wind (green) and solar energy (yellow) in Germany-09/2011[16]

As we have seen before in the power generation mix, a multitude of different power plant types are feeding the grid to satisfy the consumer needs. However, we should analyse a little bit the different power plant types in order to understand their capabilities and abilities.

[15] Cf. ENTSO-E Views on Energy Roadmap 2050; publ. 2012

[16] Andritz Hydro-Make HPPs fit to provide ancillary services-08/2012

To start with let us have a look at a typical generation curve for a week, in this example an average week of France.

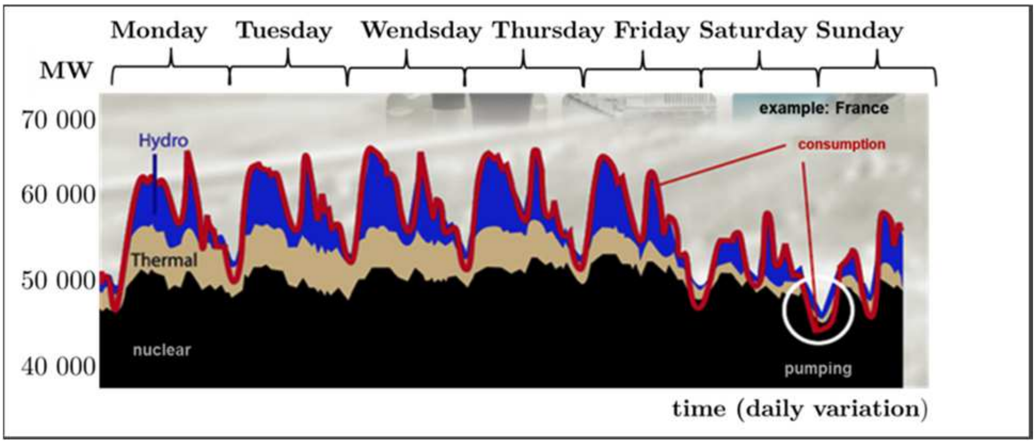


Figure 2-9 Typical generation / consumption diagram over one week[17]

Figure 2-9 demonstrates that in France the average base load is about 50 GW but over the day there are periods of nearly 70 GW with a steep increase as well as decline of the consumption. Thus, the grid and the different generation plants have to be flexible enough to satisfy those customer needs. As the economic aspect is very important, we have to understand which plants are ideal for what. Below you find a short analysis of various parameters of power plants which demonstrate the complexity of grid operations. Figure 2-10 shows a comparison of electric net efficiency over nominal electric output, obviously the efficiencies of the power plants and consequently the electric output vary a lot.

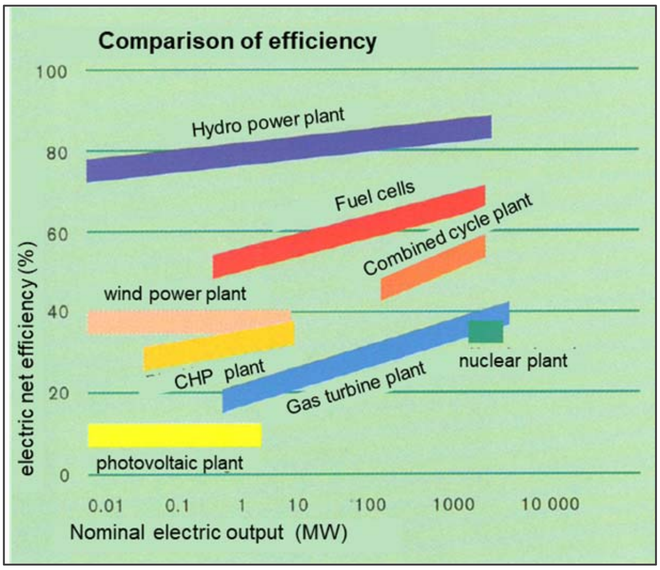


Figure 2-10 Comparison of plants efficiency over electric output[18]

[17] Andritz Hydro- Grid contol/Netzregelungs- 10/2012

[18] Ökologische (Teil A) und technisch/ökonomische (Teil B) Qualitäten der Wasserkraft, Verbandsschrift

Comparison of start-up periods:	
Power plant type	**Start-up periods**
Storage hydro power plant	0,5…4 min
Open cycle gas turbine plant	8…10 min
Combined cycle power plant	10…180 min
Oil-fired thermal plant	approx.. 1,25…5 h
Coal-fired thermal plant	approx.. 6…24 h
Nuclear power plant	approx.. 48…120 h

Table 2-1: Start-up periods of different power plants[19]

Comparison of load change gradient:	
Power plant type	**Load change gradient**
Storage hydro power plant	up to several 100 MW / min
Open cycle gas turbine plant	1…10 MW / min
Combined cycle power plant	approx. 10 MW / min
Oil-fired thermal plant	approx. 10 MW / min
Coal-fired thermal plant	approx. 10 MW / min
Nuclear power plant	approx. 10 MW / min

Table 2-2: Load change gradients of different power plants[17]

Out of the above analysis the following conclusions can be drawn:

- Thermal power plants usually are of larger size and with the exception of open cycle gas turbine-plants have a relatively long start-up period and also a limited output gradient.
- New renewables as wind, photovoltaic, even bio-mass are of smaller size and cannot significantly contribute to the grid stability support.
- Nuclear plants are the real Jumbos with regard to plant size but are extremely lethargic. They have very long start-up periods and in comparison of their power capabilities rather small output gradients.

Because of those long start-up periods nuclear and thermal stations are in general operated as base load or nearly base load plants. Run-of-river hydro plants are mostly operated as base load plants, too. Only hydro beside run-of-river hydro plants and open-cycle gas turbine plants can significantly contribute to balance the fluctuations of customer demand. Storage plants as well as gas turbine power plants are used to support load balancing and frequency control.

[19] Cf.Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

3. Hydro power plants

As already mentioned, hydro-electric power plays an important role in electric energy generation. Hydro-electric power is not only providing base load with run-of-river plants but can also provide peak load and frequency control thus significantly contributing to grid stability.

There exist a lot of different concepts, for example turbine types or machine types of different power and also different ways of power house buildings. Depending on the hydrology of the specific location or body of water different types of hydro power plants have been developed. In order to understand the requirements and the needs of a hydro power plant, a closer look into their characteristics is necessary

3.1. Basics of hydro generation

Any hydro-electric power plant (HEPP) converts the potential and/or kinetic energy of the hydraulic system via mechanic energy into electric energy.

Potential energy
The potential energy E_{pot} of a physical system is the product of mass m of the particle, the constant of gravity g and with hydraulic head H. The mass m can also be seen as the mass density ρ and the Volume V.

$$E_{pot} = m \cdot g \cdot H \quad \text{respectively} \quad E_{pot} = g \cdot H \cdot \rho \cdot V \tag{3.1}$$

At conventional HEPPs we use for H the difference of the potential energy between upper reservoir and lower reservoir.

Based on that we get the available energy between two points as:

Kinetic energy
The kinetic energy, which an object has due to its motion, corresponds to the work required to bring the object from standstill to the actual motion. It depends on the mass m, the speed v, respectively the moment of inertia J and the angular velocity ω of the object in motion.

$$E_{kin} = \underbrace{\frac{m \cdot v^2}{2}}_{\text{translation part}} + \underbrace{\frac{J \cdot \omega^2}{2}}_{\text{rotational part}} \tag{3.2}$$

As we do not consider water particles with rotation the expression with can be reduced to

$$E_{kin} = \frac{m \cdot v^2}{2} \quad \text{respectively} \quad E_{kin} = \frac{\rho \cdot V \cdot v^2}{2} \tag{3.3}$$

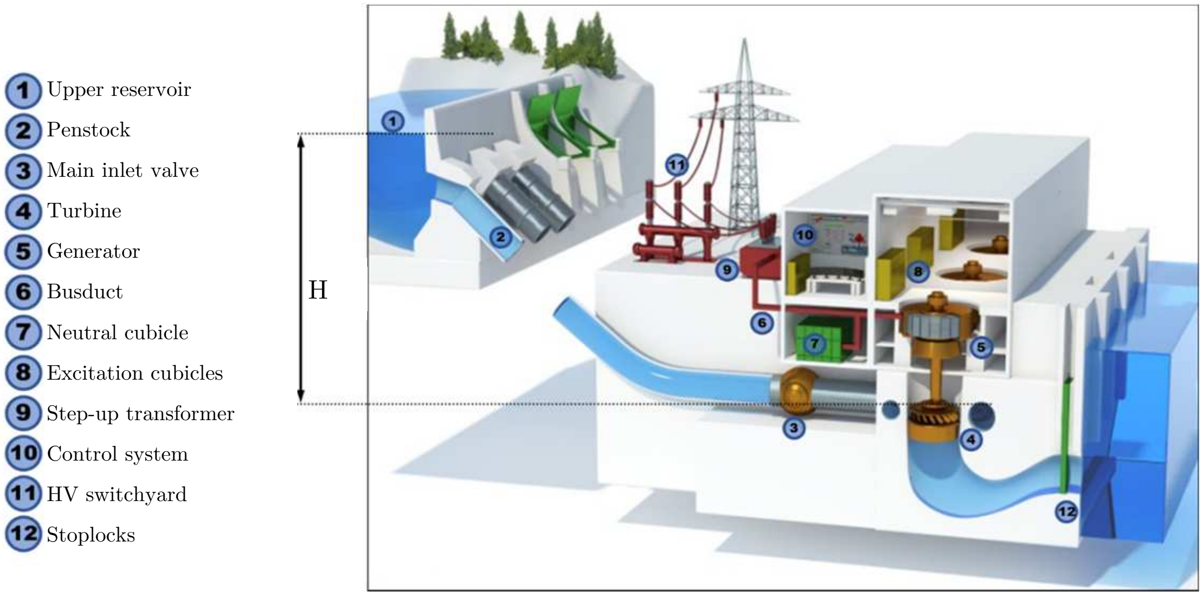


Figure 3-1 Details of a typical storage power plant[20]

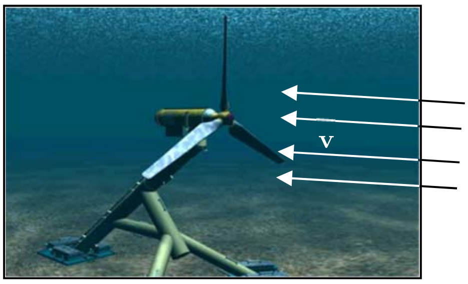


Figure 3-2 Water turbine-kinetic energy usage[20]

At other RES, as e.g. for marine currents or wind we use the kinetic energy of the surrounding fluid.

In the following chapter we will see the different major types of hydro-electric power plants.

[20] Cf. Andritz Hydro-Make HPPs fit to provide ancillary services-08/2012

3.2. Power plant types

There are many types of hydro-electric power plants, not only characterised by the turbine and generator parameters but also by general parameters such as hydrologic parameters, location parameters and parameters of the power plant itself.

Hydrologic parameters

- Mass quantity, flow characteristic
- Potential annual generation
- Water quality

Location parameters

- Altitude above sea level
- Average temperature of the water
- Climate
- Sedimentation

Parameters of power plant

- Number of units
- Orientation of axis
- Mounting depth
- Force transmission
- Etc..

All of these parameters and some more are decisive for a hydro-electric power plant. Therefore, many different types respectively designs or concepts of hydro-electric power plants are existing. In order to have a look at the major power plant types five concepts of those are described below.

3.2.1. Run-of-river power plant[21]

Run-of-river power plants are very common in Austria and as already mentioned above used as base load producers. Under normal operation the full available water flow of the river passes through the turbines in a run-of-river power plant. Although the exact flow rate isn't known a water level control regulates the water level that keeps it constant. If it is raining and the water level increases the control opens the turbine guide vanes to let more water flow through the turbine. In case the river flow exceeds the nominal flow rate of the turbines the gates will be opened to let the water through thus bypassing the turbines. In case of low flow the water level will

[21] Cf. https://www.wasserkraftverband.de/pages/wissenswertes-zur-wasserkraft/verschiedene-arten-von-wasserkraftwerken.php

decrease when operating the turbines at nominal flow. In order to keep the water level the control device will reduce the flow through the turbine or in case of a multi-unit power plant one unit or even more units will be taken out of service. Level control on the Danube is rather strict as to keep sufficient river depth for navigation.

In Austria, the largest run-of-river power plants are located at the Danube river. It has to be mentioned that by means of specific Q-time diagrams different types of rivers can be identified. Figure 3-3 shows different characteristics dependent on the normalised flow characteristics. Central alp rivers are characterised by a very high flow but only for a short amount of days in contrast to inner alpine rivers and the Danube river which are characterised by much higher average flow over the year.

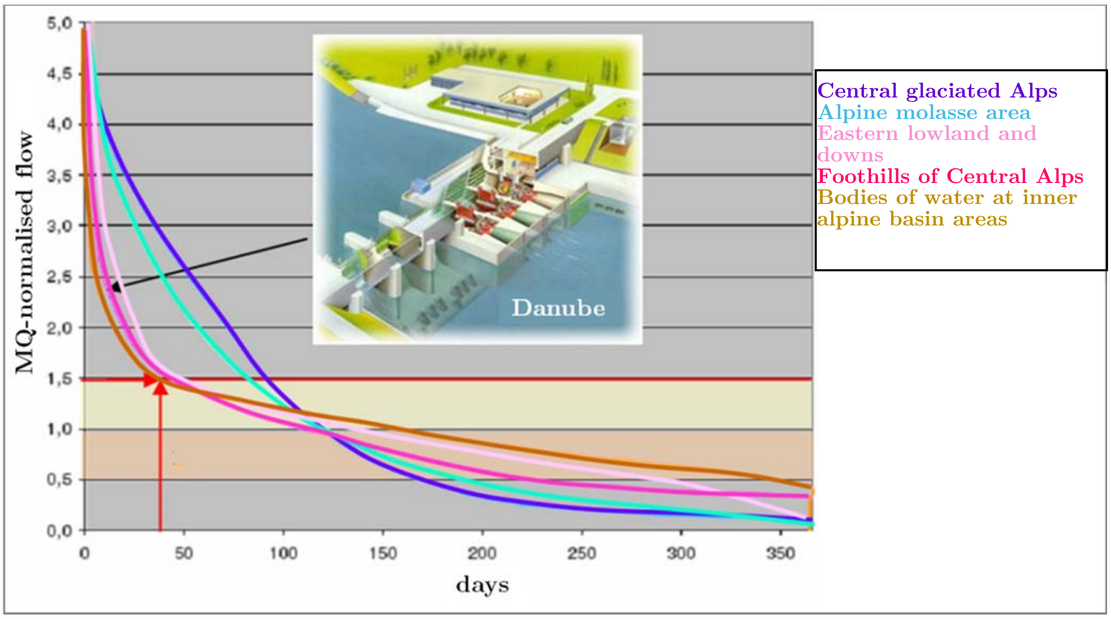


Figure 3-3 Mass quantity diagram of typical rivers in europe[22]

3.2.2. Storage power plant[23]

A storage power plant is characterised by its dam. In most cases it is built by human hand although some are also made by nature. The dam retains the inflowing water thus creating a storage reservoir. The maximum amount of water which can be stored and the hydraulic head are the deciding factors how much energy can be stored in the reservoir.

Storage power plants are used to shift the generation to high load periods whereas in low load times water will be collected.

In storage power plants, we differentiate between plants with pure storage operation capability and those who collect the already used water in a reservoir below the

[22] Cf. Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

[23] Cf. https://www.wasserkraftverband.de/pages/wissenswertes-zur-wasserkraft/verschiedene-arten-von-wasserkraftwerken.php

power plant and then pump it up again at low load periods, so-called pumped storage power plants. Figure 3-4 shows a section of a typical storage power plant.

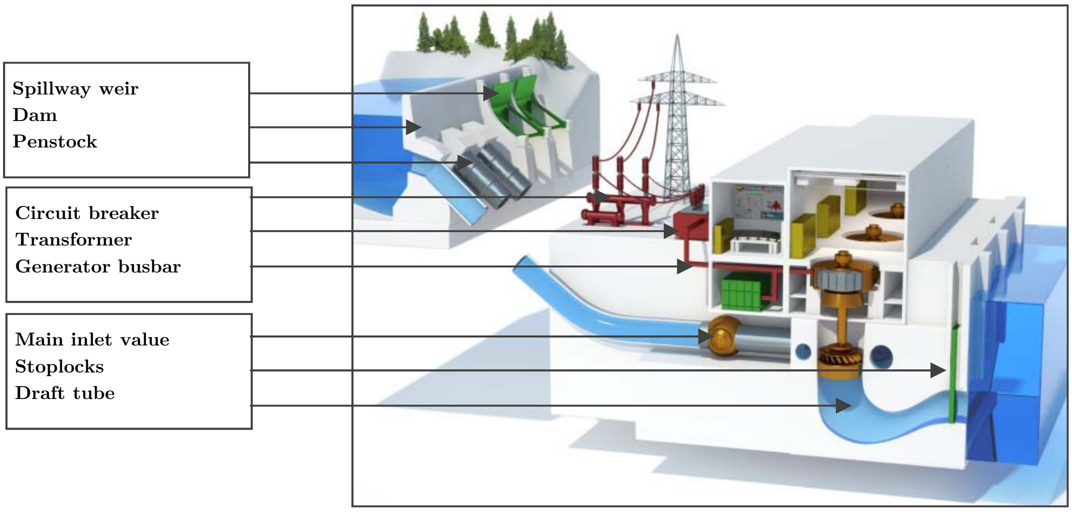


Figure 3-4 Storage power plant[24]

3.2.3. Pumped storage power plant[25]

As already addressed before, Storage power plants which save the used water in impounding reservoirs underneath the power plant and use it later to pump it up to the main reservoir under low energy cost conditions are called pumped storage power plants.

During many decades, mostly until the second half of the 20th century the role of pumped storage power plants was to act as pure storage of the energy produced in excess of the consumption (mostly during night) by thermal power plants (nuclear, coal and oil) or even by run-of-river hydro-electric power plants.

However, the deregulation and liberalization observed in the market place as well as the environmental and sustainability issues have dramatically changed the role of pumped storage power plants from the classical pure storage function to a dynamic grid support function.

The integration of a fast-growing portion of “new” renewable energy sources – like wind and solar - into existing grid topologies brings new requirements and challenges in particular on the design of the electric machinery, e.g. the motor-generator, used in pumped storage power plants. Moreover, new challenges are made for the electrical behaviour of the motor-generator during specified electrical faults and grid scenarios. The dynamic grid support function is also one of the reasons, why more and more

24 Cf. Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

25 Cf. https://www.wasserkraftverband.de/pages/wissenswertes-zur-wasserkraft/verschiedene-arten-von-wasserkraftwerken.php

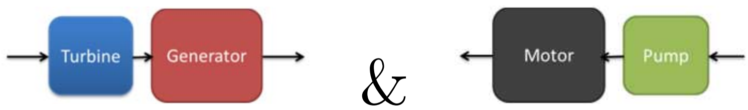
new pumped storage schemes are planned and built with the variable speed technology. Also, the compensation for ancillary services, like power regulation (consumption) in the motor-pump mode might be a strong incentive for the use of the variable speed technology.

With the fast development and large-scale use of power electronics, variable speed electric machinery has become very popular for industrial drives in the last 20 years and has also opened the way for variable speed power units especially in pumped storage power plants.[26]

The speciality of a pumped storage power plant is to act as energy saver and hydro power generator at the same time. If the grid needs electric energy the plant is operated in turbine/generation mode whereas if there is an energy surplus the pumped storage power plant is working in pumping/motor mode. The motor/generator drives the pump or pump-turbine and water is pumped from the lower reservoir into the upper reservoir, to refill it again.

In principal there are three different concepts for a pumped storage power plant:

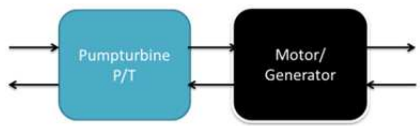
- The trivial design



In former times, some of the first pumped storage power plants have had this arrangement. As shown there are two different machine sets. One set is for energy generation (turbine - generator set) and the second is for pumping (pump – motor set). Obviously this concept is not the most economical way to design a pumped storage power plant because of the two separate sets.

Another form is the most commonly used:

- Reversible design



In this design, turbine and pump as well as motor and generator are combined in each one element namely a pump-turbine and a motor/generator. Thereby turbine mode and pumping mode can have the same direction of rotation or different directions of rotation. For the start-up in pumping mode, additional equipment is always with such arrangements.

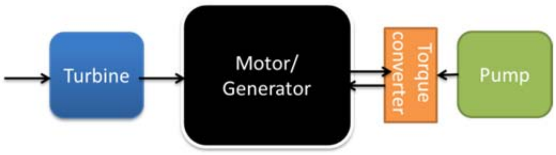
[26] Cf. HYDRO 2013; Modern Design for Variable Speed Motor-Generators- Thomas Hilinger

Costs of reversible generation sets are more expensive than single direction motor/ generator or a pump/turbine sets but one set can be spared saving more than the additional costs of a reversible unit, even considering the higher maintenance requirements. Because of the combination of pump and turbine in one single unit a compromise in the hydraulic design has to be made.

The figure above shows the two ways of operating a pumped storage power plant with two combined elements. If the pump-turbine is working in the turbine mode the generator is generating power but if the pump-turbine has to change into pumping mode the machine set has to be shut down and run-up into the other direction of rotation which causes mode change periods of several minutes. Although the reversible design seems to be probably the most economic one there are aspects which another concept can fulfil better.

If we need fast mode changes another design is more suitable:

- Ternary design



This design enables short mode changes. Instead of only two machine elements three elements are used which are linked by a common shaft. The turbine and the pump rotation directions are the same. Because of the separation of pump and turbine both elements can optimally designed to achieve maximum of efficiency. While the torque converter is not enabled the water flows through the turbine and the generator converts the mechanic energy into electric energy. In pumping mode the torque converter is enabled and the turbine guide vanes close the water inlet to the turbine and the runner chamber will be blown out by pressurised air so that the turbine runner spins only in air and creates much less friction losses than in water.

Another speciality of the ternary concept is the hydraulic short circuit operation mode where generation and pumping is possible at the same time. However, it has to be mentioned that this is a very maintenance intensive operation.[27]

Figure 3-5 shows a scheme of a ternary type pumped storage power plant. In generation mode the water flows from the upper reservoir through penstock and the turbine to the lower reservoir. Otherwise in pump mode the water flows from the lower reservoir through the pump and the penstock back to the upper reservoir.

[27] Cf. https://www.tugraz.at/fileadmin/user_upload/Events/Eninnov2018/files/kf/Session_C2/KF_Holzer.pdf

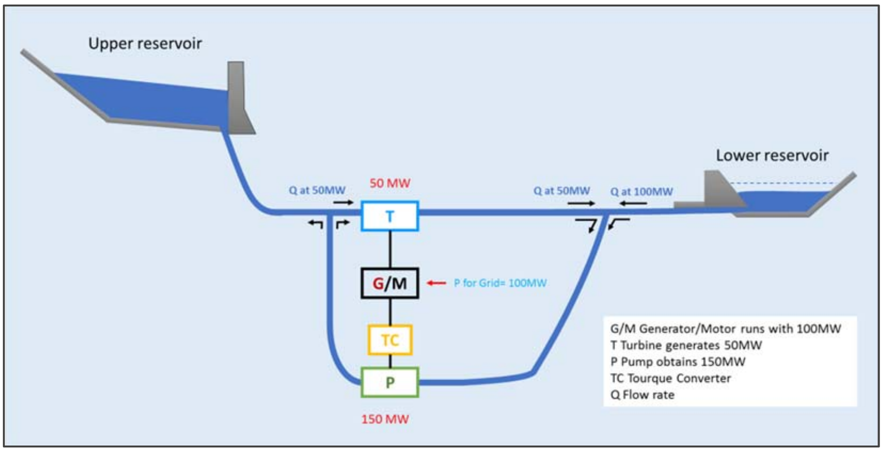


Figure 3-5 Scheme of a pump storage power plant ternary unit[28]

In turbine mode, the generated active power can be regulated by controlling the water flow across the turbine by means of guide vane opening angle. In pumping mode, the pumped power is constant due to the fixed operating frequency of the grid connected motor/generator. The only option to control the power absorbed of a fixed speed unit is a hydraulic short circuit.

3.2.4. Tidal power plant / ocean currents

Tidal power is using the movements of the water masses of the oceans due to the gravitational changes of the different positions of earth and moon and sun over the day/week/month/year. The potential and kinetic energy of those water movements can be used in tidal power plants. The potential power with the rising and falling sea levels per day is generating electricity. Compared to the former shown plant types, in tidal power plants the water flows into both directions, in and out of the turbine.

Because of this bidirectional flow, the tidal power plant can generate power when the water is flowing in and also when it is ebbing out. In general, we differentiate between two types:

- Tidal barrages which uses the tide difference to convert analogue to a storage plant the potential energy of the tide stored into electricity
- Tidal current power plants (and also ocean currents) have no dam structure. They just use the water velocity (the kinetic energy) to convert it into electricity. To better describe the concept one can say "underwater wind farm" as the technology used is comparable to plants used in the wind industry. Ocean current plants use the same concept but only one-directional.[29]

[28] Cf. Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

[29] Cf. http://www.alternative-energy-tutorials.com/tidal-energy/tidal-energy.html

Tidal barrages

The tidal barrage power plant uses a structure similar to a dam called a barrage. The barrage is installed across an inlet of an ocean bay or lagoon that forms a tidal basin. Sluice gates on the barrage control water levels and flow rates to allow the tidal basin to fill on the incoming high tides and to empty through an electricity turbine system on the outgoing ebb tide.[30]

Figure 3-6 Sihwa lake tidal power station, South Korea

Figure 3-6 shows the Sihwa lake tidal power plant, it is located in South Korea at the Sihwa lake. It started commercial operation in 2011 and has a 12.5 km long seawall. The power generation is based on a tidal inflow driving the ten 25.4 MVA submerged bulb turbines into the 30 km^2 basin. It is the world's largest tidal power plant with a capacity output of 254 MVA.[31]

Tidal current

The motion of the tidal water, driven by the pull of gravity, contains large amounts of kinetic energy in the form of strong tidal currents called tidal streams. The daily ebbing and flowing is different all over the world. The biggest tides can be found at Newfoundland, at west Britain's coasts and at the northwest coast of France, they are between 15…18 m as a maximum. As a result a high amount of turbines are required to generate a high capacity output.[32]

This technology is very young and only a few installations, e.g. at the EMEC test facility in the north of Scotland are in commercial operation.

[30] Cf. https://www.eia.gov/energyexplained/hydropower/tidal-power.php

[31] Cf. https://www.power-technology.com/features/featuretidal-giants-the-worlds-five-biggest-tidal-power-plants-4211218/

[32] Cf. http://www.alternative-energy-tutorials.com/tidal-energy/tidal-energy.html

3.2.5. Wave power plant[33]

Wave power plants use the capture of energy of wind waves to do useful work e.g. electricity generation, water desalination or pumping water. A machine that exploits wave power is a wave energy converter.

Wave power is different from tidal power which captures the energy of the current caused by the gravitational pull of sun and moon. Waves and tides are also different from ocean currents which are caused by other forces including breaking waves, wind, the Coriolis effect, cabbeling and differences in temperature and salinity.

There are many concepts to convert the wave energy into electricity however for our considerations of variable speed generation those concepts are not relevant as either the capacity is too small or the conversion is not performed by a hydraulic turbine-generator set.

Figure 3-7 Wave energy converter[34]

3.3. Turbines

A turbine is a rotating mechanical device that extracts energy from a fluid flow (kinetic energy and/or potential energy) and converts it into useful work. The work produced by a turbine can be used for generating electrical power when combined with a generator.[35]

Turbines are a major element in the power chain of hydro power generation. They are characterised with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. Water turbines have a casing around the blades that contains and controls the working fluid. A working fluid contains potential energy (pressure head) and kinetic energy (velocity head). The fluid may be

[33] Cf.https://www.wasserkraftverband.de/pages/wissenswertes-zur-wasserkraft/verschiedene-arten-von-wasserkraftwerken.php

[34] ScottishPower Renewables https://earthtechling.com/2011/11/wave-power-array-to-get-real-world-test

[35] Munson@all, "Turbomachines." Fundamentals of Fluid Mechanics. 6th ed. Hoboken, NJ: J. Wiley & Sons, 2009

compressible or incompressible. Several physical principles are employed by turbines to collect this energy:

Impulse turbines change the direction of flow of a high velocity fluid jet. The resulting impulse spins the turbine and leaves the fluid flow with diminished kinetic energy. There is no pressure change of the fluid or gas in the turbine blades (the moving blades), as all the pressure drop takes place in the stationary blades (the nozzles). Before reaching the turbine, the fluid's pressure head is changed to velocity head by accelerating the fluid with a nozzle. Pelton turbines use this process exclusively. Impulse turbines do not require a pressure casement around the rotor since the fluid jet is created by the nozzle prior to reaching the blades on the rotor. Newton's second law describes the transfer of energy for impulse turbines. Impulse turbines are most efficient for use in cases where the flow is low and the inlet pressure is high. Newton's second law states that the rate of change of momentum of a body is directly proportional to the force applied, and this change in momentum takes place in the direction of the applied force. The net force F applied is the derivative of the impulse p with respect to t, the impulse p itself is the product of mass of the body m and its velocity v and in case of in-compressive fluid the mass m is constant, and the force F can be expressed as product of mass m and body's acceleration a.

$$F = \frac{\partial p}{\partial t} = \frac{\partial (mv)}{\partial t} \underset{\text{in-compressible fluid}}{\overset{\text{in case of}}{}} = m\frac{\partial v}{\partial t} = ma \tag{3.4}$$

Reaction turbines develop torque by reacting to the fluid's pressure or mass. The pressure of the fluid changes as it passes through the turbine rotor blades. A pressure casement is needed to contain the working fluid as it acts on the turbine stage(s) or the turbine must be fully immersed in the fluid flow (such as with wind turbines). The casing contains and directs the working fluid and, for water turbines, maintains the suction imparted by the draft tube. Francis turbines use this concept. Newton's third law describes the transfer of energy for reaction turbines. Reaction turbines are better suited to higher flow velocities or applications where the fluid head (upstream pressure) is low.

In order to obtain the highest power or best efficiency every hydro power plant has its own parameters and consequently specific hydraulic layout. To properly size a hydro power plant output there are two major parameters,

- Flow rate Q and
- Hydraulic water head H

which lead to specific speed n_q

$$n_q = n\left(\frac{H}{H_{nom}}\right)^{-\frac{5}{4}} \sqrt{\frac{P_{nom}}{Q_{nom}H_{nom}}\frac{1}{\sqrt{g\rho\eta}}} \tag{3.5}$$

with the net hydraulic head H, flow rate Q, density of the water ρ, gravity acceleration g and the efficiency of the hydro power plant η.

The nominal output of the turbine P_{mech} is:

$$P_{mech} = \rho \cdot g \cdot H \cdot Q \cdot \eta_{mech} = \omega \cdot M \tag{3.6}$$

Another definition of specific hydraulic speed of a turbine is derived from the required power:

$$\underbrace{n_s = \frac{n\sqrt{P}}{\sqrt{\rho}(gH)^{\frac{5}{4}}}}_{\text{dimensionless specific speed}} \qquad \underbrace{n_s = n\sqrt{\frac{P}{P_{nom}}}\left(\frac{P_{nom}}{QH_{nom}g\rho\eta}\right)^{-\frac{5}{4}}}_{\text{dimensioned specific speed}} \tag{3.7}$$

Number	n_S [p.u.]	Type of turbine with best efficiency
1	80…295	Pelton wheel with single jet
2	295…500	Pelton wheel with multi jet
3	500…2500	Francis turbine
4	2500…9000	Kaplan turbine

Table 3-1 Turbine applications[36]

For the proper design the operation parameters for the intended operation range as nominal head H_n at nominal flow Q_n as well as variation of head and flow and intended operating hours for pump and turbine operation are needed. Out of that the optimisation of the efficiency, the operating range which is limited by cavitation and stability result in the generated respectively consumed energy per year.

[36] Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

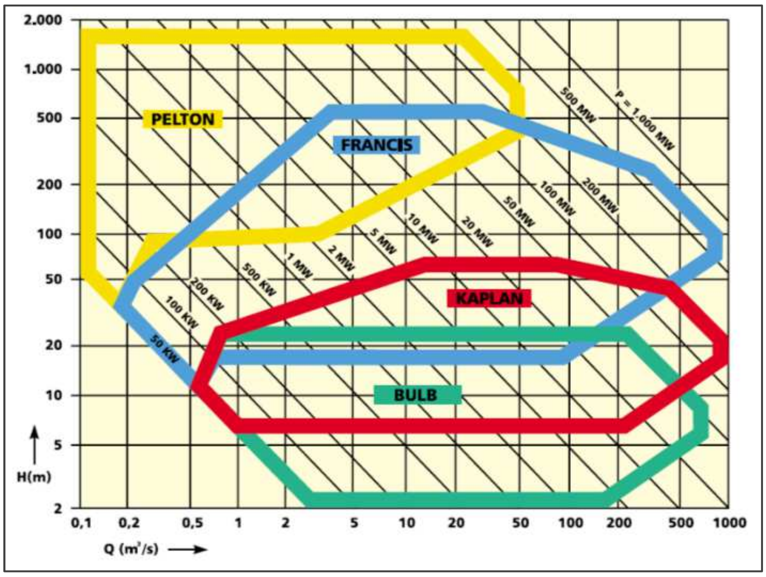


Figure 3-8 Turbine types and their application ranges[37]

Flow rates and hydraulic head vary a lot from location to location and therefore different turbine types are necessary. Figure 3-8 shows the different application ranges of the turbines dependent on flow rates and net hydraulic head. The major turbine types are called Pelton, Francis and Kaplan. Another form of Kaplan turbine is the bulb turbine which is more or less a horizontal axis Kaplan turbine totally surrounded by water. It shows that bulb and Kaplan turbines are used at low hydraulic head and large flow while Pelton turbines are used in case of low flow rate and large hydraulic head. Francis turbines cover the field in between and are by far the most used turbine type. Figure 3-9 shows the efficiency characteristics of various turbines over percentage of rated load with the specific speed of the turbine as parameter. It can be seen that Pelton turbines have the best part load characteristic while propeller type turbines (e.g. Kaplan turbines with fixed blades) have only a good efficiency in the vicinity of the design point.

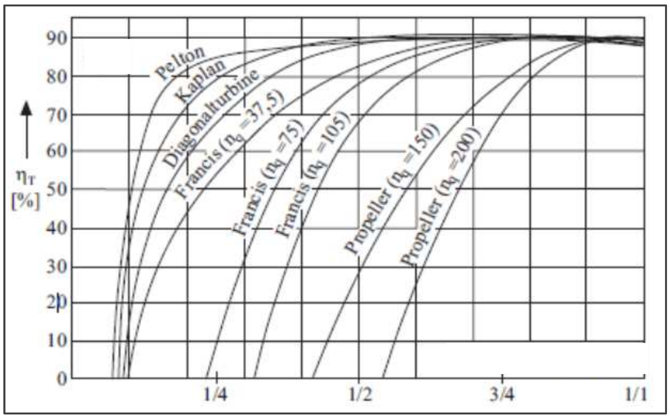


Figure 3-9 Part load efficiencies of different turbine types[38]

[37] Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

[38] Stand der Technik von Pumpspeicheranlagen- Tugraz.pdf

3.3.1. Pelton turbine[39]

The Pelton turbine is an impulse water turbine with a tangential flow. The turbine extracts energy from the water jet impulse. The potential energy of the water is transformed into kinetic energy of the jet speed. The turbine receives its water flow in a curved duct that surrounds the actual moving element, the runner. Stationary nozzles direct the water tangentially in sharp jets onto the runner. The runner carries double spoon-shaped buckets which are located at the outside of the turbine rotor. When the water hits the centre of the bucket the water is guided from the inner side to the outer side of the bucket following the shape of the buckets. The impulse energy is set free and the water exits at the outer side of the bucket in nearly revised direction. The Pelton turbine is designed for high hydraulic head and low flow rates.

Figure 3-10 Pelton turbine[40]

Figure 3-10 shows the world largest Pelton turbine of the power plant in Bieudron, Switzerland. The turbine parameters are **H = 1869 m, n = 428,6 rpm; P = 423 MW**. As shown in Figure 3-8 the Pelton turbines are used for very high hydraulic heads with a low flow. Consequently the specific hydraulic speed is rather low in contrast to the high mechanical speed. For different applications the Pelton turbine is scaled into low, normal and fast speed turbines with their specific hydraulic speed shown in Table 3-2.

Pelton turbine	Specific hydraulic speed n_S[p.u.]
Low-speed-turbines	80...110
Normal-speed-turbines	150...160
Fast-speed-turbines	200...300

Table 3-2 Specific hydraulic speed of different Pelton turbine types

[39] https://www.encyclopedia.com/manufacturing/encyclopedias-almanacs-transcripts-and-maps/turbines-wind-hydropower

[40] Pelton runner- Bieudron, Switzerland- ResearchGate

Figure 3-11 shows a typical characteristic of the Pelton wheel with a single jet, the best efficiency point is at a specific hydraulic speed between 80...295.
Figure 3-12 instead shows the typical characteristic for the Pelton turbine with multiply jets where the best efficiency lies between a specific hydraulic speed of 295...500.

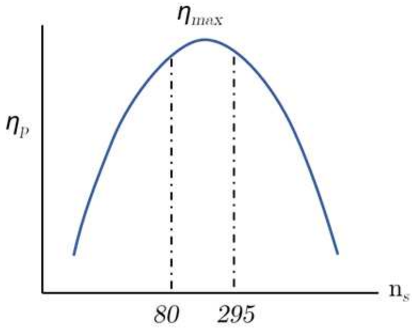


Figure 3-11 Speed-efficiency characteristic of a Pelton wheel with single jet[41]

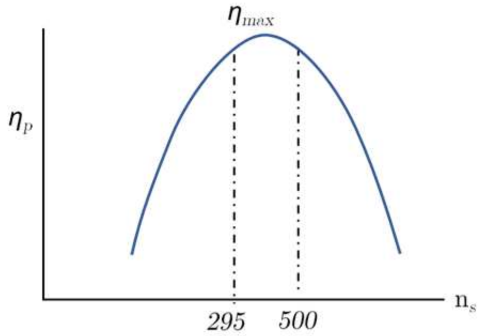


Figure 3-12 Speed-efficiency characteristic of a Pelton wheel with multi jet[41]

3.3.2. Francis turbine[42]

The Francis turbine is nowadays the most commonly installed water turbine which converts kinetic and pressure energy of the fluid into mechanical energy of the runner. The Francis turbine as shown in Figure 3-13 is a reaction turbine, where the working fluid enters the turbine with high pressure respectively high velocity and the energy is extracted by means of expansion with speed reduction between the turbine blades from the working fluid. A part of the energy is converted by the fluid because of pressure changes occurring in the blades of the turbine, quantified by the expression of degree of reaction, while the remaining part of the energy is extracted by the volute casing of the turbine. In the spiral casing the water gets a swirl when entering radially into the runner and leaves axially. Application area is from 40 to 600 m hydraulic head. Francis turbines can also be used as a pump when rotating in the reverse direction.

[41] Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/201

[42] https://www.encyclopedia.com/manufacturing/encyclopedias-almanacs-transcripts-and-maps/turbines-wind-hydropower

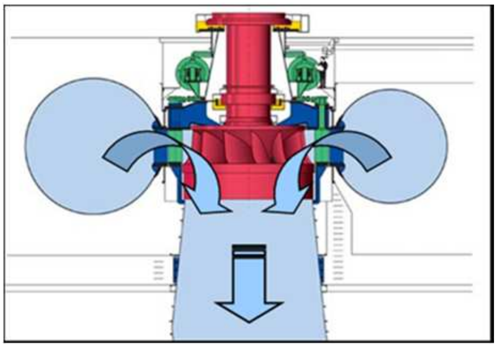


Figure 3-13 Francis turbine[43]

Francis turbines are categorised into low, normal, fast, very fast and express speed turbines with different specific speeds, as shown in Table 3-3. It can be seen that there exist also express-type runner with a maximal specific hydraulic speed from 4000-6000.

Francis turbine	Specific hydraulic speed n_S[p.u]
Low-speed-type	500...1500
Normal-speed-type	1500...2500
Fast-speed-type	2500...3500
Very fast-speed-type	3500...4000
Express-type runner	4000...6000

Table 3-3 Specific hydraulic speed of different Francis turbine types[42]

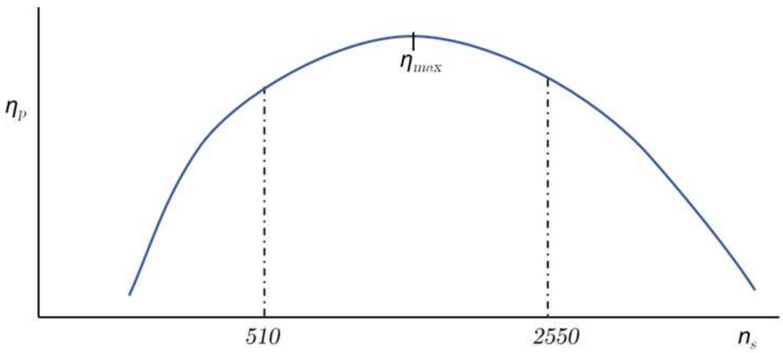


Figure 3-14 Speed-efficiency characteristic of a typical Francis turbine[42]

Figure 3-14 shows the speed efficiency characteristic of a typical Francis turbine. The Francis turbine has its best speed efficiency at a wide range of the specific hydraulic speed between 510...2550.

[43] Cf. Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

3.3.3. Kaplan turbine[44]

The major difference between the Kaplan turbine and the Pelton or Francis turbine are the adjustable blades of the turbine runner. This has a big advantage by variable operating hydraulic head and flow conditions. Because of this flexibility efficiency of 80 to 95 % can be achieved.

The Kaplan turbine is a variable-blade propeller-type turbine or an inward flow reaction turbine, which means that the working fluid changes pressure as it moves through the turbine and converts its energy. Power is recovered from both the hydrostatic head and from the kinetic energy of the flowing fluid.

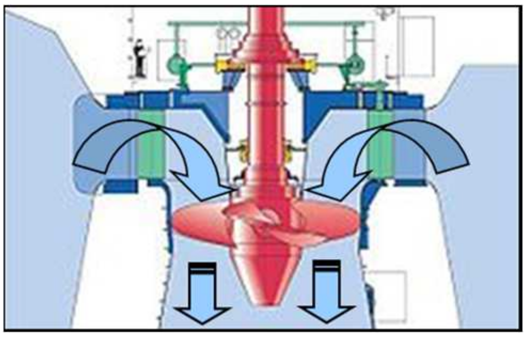


Figure 3-15 Kaplan turbine[43]

Figure 3-15 shows a Kaplan turbine section and conversion process. The inlet is the so-called spiral casing containing the turbine's fixed stay vanes and the movable wicket gates (also named guide vanes) evenly distributed around. The water enters radially through the wicket gate openings and gets a spin in the spiral casing. Then the water is deflected by 90° spirals axially through the runner with the blades.[45]

As seen in Figure 3-8 the Kaplan turbine is for variable or small hydraulic heads and high flow rates with low hydraulic head power production. The Kaplan turbine is separated into low, normal and fast speed turbines, as listed in Table 3-4. It is noticeable that the specific hydraulic speed is higher than in the previously discussed turbines.

Kaplan turbine	Specific hydraulic speed n_S[p.u.]
Low-speed-turbines	3000...6000
Normal-speed-turbines	4000...9000
Fast-speed-turbines	4000...15000

Table 3-4 Specific hydraulic speed of different Kaplan turbine types[42]

[44] https://www.verbund.com/de-at/ueber-verbund/kraftwerke/turbinen/kaplan

[45] Dietrich Oeding, Bernd R. Oswald: Elektrische Kraftwerke und Netze. Springer 7. Auflage 2011

3.3.4. Bulb turbine[46]

Another type of a Kaplan turbine is the bulb type turbine. The turbine and the generator are arranged in a torpedo shaped bulb completely submerged and fixed into a water channel (Figure 3-16). The bulb type turbine is more or less a horizontal axis type of the Kaplan turbine and has a much better efficiency at hydraulic heads below 25 m as shown in Figure 3-8. The maintenance of the generator is more difficult because of the limited space and access into the bulb. Another disadvantage is the rather low moment of inertia of the rotating units compared to a vertical unit. Nevertheless the bulb turbine has an extraordinary flexibility in its application. Therefore, it can be used from small to large sizes, in a run-of-river and/or tidal power plant at fixed and variable-speed concepts, too. Kaplan as well as bulb type turbines can be used as a pump when operating in reversed speed direction.

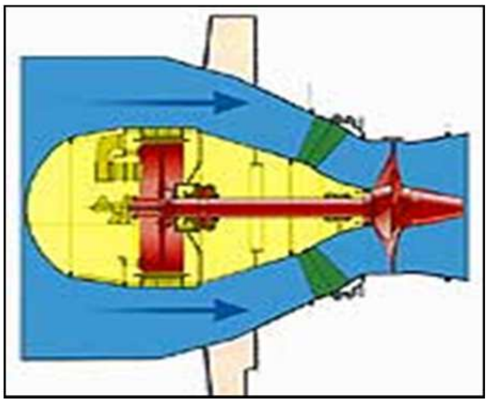


Figure 3-16 Bulb turbine[47]

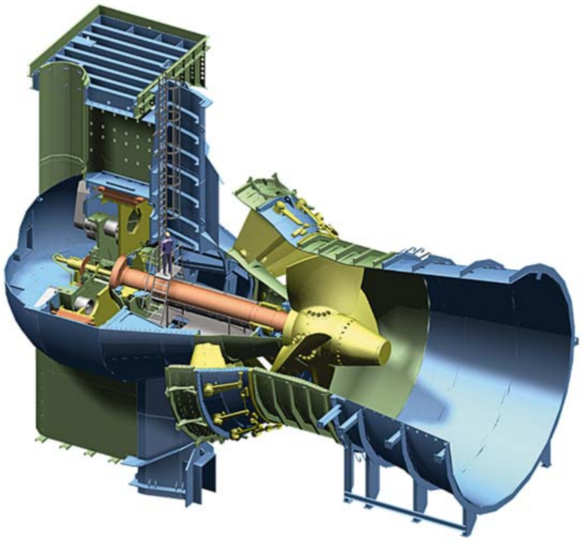


Figure 3-17 Bulb turbine 3D view[47]

[46] https://www.sciencedirect.com/topics/engineering/bulb-turbines

[47] https://www.andritz.com/hydro-en/hydronews/hydro-news-29/hy-news-hn29-13-bulb-turbines-hydro

3.4. Pumps/Pump-turbines[48]

As previously explained today's pumped storage power plant concepts are of the ternary or the reversible design. At the ternary design a turbine and a pump are used with a clutch or a torque converter in between to decouple the two machines, all with the same sense of rotation. At the reversible design solely a pump-turbine is used, one sense of rotation for turbine operation the other sense of rotation for pump operation.

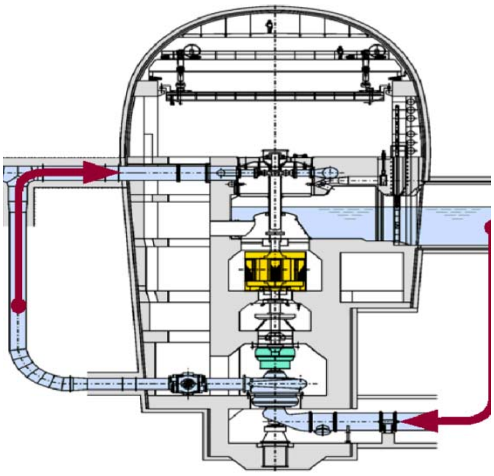


Figure 3-18 Ternary design-pump and turbine[49]

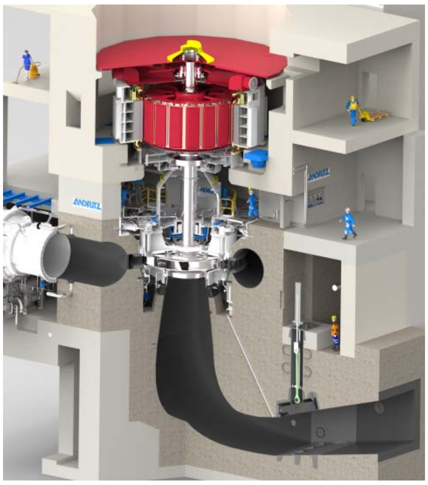


Figure 3-19 Reversible design-pump-turbine[50]

Large scale pumps for the application in power station are usually of the axial-flow pump type which has essentially the same operating principles as centrifugal pumps. When a casing contains only one revolving impeller, it is called a single-stage pump. When a casing contains two or more revolving impellers, it is called a doubly-or multi-stage pump.

Some water turbines are designed as a pump-turbine. When a reaction turbine reverses sense of rotation and direction of flow it operates as a pump. A centrifugal pump uses an impeller with backward-swept arms.

[48] http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

[49] https://www.researchgate.net/figure/Ternary-PT-with-possibility-to-operate-in-hydraulic-short-circuit_fig19_265907090

[50] Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/201

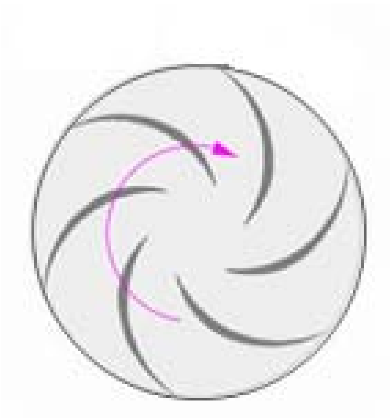


Figure 3-20 Pump impeller[51]

As we will later discuss primarily pumped storage applications a more detailed look into the physics of centrifugal pumps should help to better understand the advantages of variable speed operation.

3.4.1. Pumping system hydraulic characteristics[52]

In a pumping system, in most cases the objective is either to transfer a liquid from a source to a required destination, e.g. filling a high-level reservoir, or to circulate liquid around a system, e.g. as a means of heat transfer. Pressure is needed to make the liquid flow at the required rate and this must overcome losses in the system. Losses are of two types: static and friction head. Static hydraulic head, in its most simple form, is either the difference in height of the supply and destination of the liquid being moved or the pressure in a vessel into which the pump is discharging, if it is independent of the flow rate. Friction head (sometimes called dynamic head loss) is the friction loss on the liquid being moved in pipes, valves and other equipment in the system. This loss is proportional to the square of the flow rate. A closed-loop circulating system, without a surface open to atmospheric pressure, would exhibit only friction losses.

Centrifugal pumps are used on many industrial and commercial applications. Many of these pumps are operated at fixed speeds, but could provide energy savings through variable speed operation as we will discuss later. Pumps at fixed speed have significant limitations: pumps are not controllable; the operating point is defined by the system characteristic and the pump characteristic (resp. the required net head). Power consumption variation is only due to changes of net head due to reservoir level fluctuations.

Reviewing the affinity laws for centrifugal pumps and a typical operating cycle for a centrifugal application will show this.

[51] Cf. http://www.research.net

[52] http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

These relationships can also be expressed numerically as shown in Table 3-5. Theoretically, it would be possible to operate at 50% flow with only 13% of the power required at 100% flow. Since the power requirements decrease much faster than the reduction in flow, the potential exists for significant energy reduction at reduced flows.

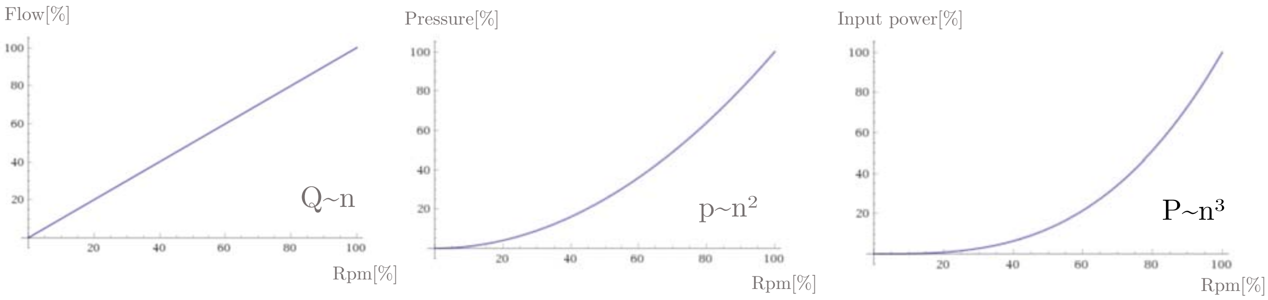


Figure 3-21 Centrifugal pumps affinity laws[53]

Speed [%]	Flow [%]	Power required [%]
100	100	100
90	90	73
80	80	51
70	70	34
60	60	22
50	50	13
40	40	6
30	30	3

Table 3-5 Relationships between speed/flow and power[54]

An understanding of the basic operating characteristics of centrifugal pumps is necessary to understand later variable frequency application. The pump is described by a system curve which can be defined as the relationship between flow and hydraulic head in a fixed hydraulic network. Figure 3-22 shows a centrifugal pump curve describing the hydraulic head (or pressure) versus flow characteristics of a typical centrifugal pump. This curve shows that the centrifugal pump will produce limited flow if applied to a piping system in which a large pressure difference is required across the pump to lift the liquid and overcome resistance to flow (as at point A). Higher flow rates can be achieved as the required pressure difference is reduced (as at point B).

[53] Cf. http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

[54] Cf. Andritz hydro- Bestimmende Parameter für Wasserkraftwerke- 06/2018

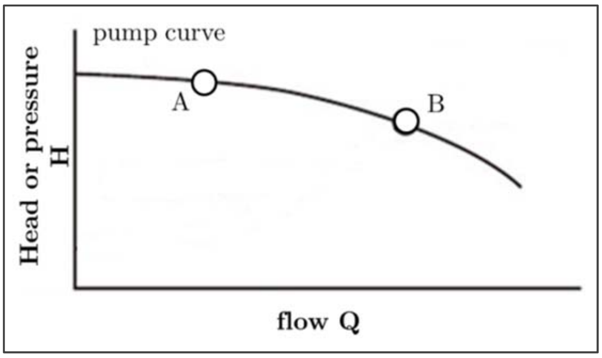


Figure 3-22 Typical centrifugal pump curve[55]

To determine where along this curve the centrifugal pump will operate in a given application requires the additional information provided by the system curve. This curve, shown in Figure 3-22 represents the characteristics of the piping system to which the centrifugal pump is applied. The hydraulic head required at zero flow is called the static head or lift.

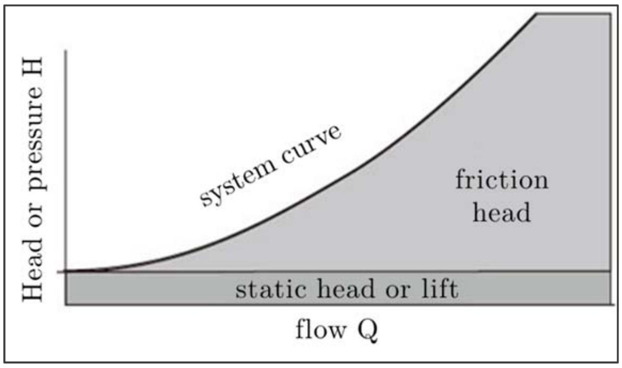


Figure 3-23 System curve[55]

Figure 3-23 shows how many meters of elevation that the centrifugal pump must lift the fluid regardless of the flow rate. Another way to describe static head is to think of it as the amount of work needed to overcome the effects of gravity.

The other component of hydraulic head is called the friction head and increases with increasing flow. Friction head is a measure of the resistance to flow (back pressure) provided by the pipe and its associated valves, elbows and other system elements.

The intersection of the centrifugal pump and system curves shows the natural operating point for the system without flow control, as shown in Figure 3-24. This intersection would generally be chosen to ensure that the centrifugal pump is operated at or near its best efficiency point.

[55]Cf. http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

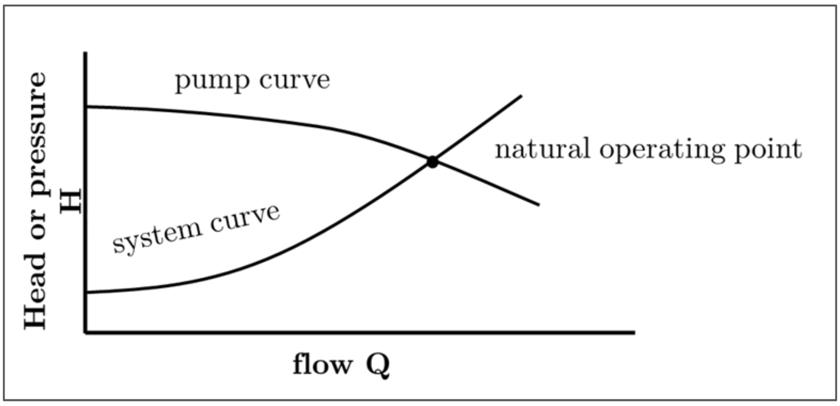


Figure 3-24 Combined curves[55]

3.4.2. Pump-turbines

To determine the size of a pump-turbine some basic input data is required. Variation of the upper and lower reservoir level flow available or power required and the hydraulic head losses are essential in order to start the layout.

The hydraulic layout of a pump-turbine is done as a pump. The maximum pump net hydraulic head is determined by adding the head losses to the static head while in turbine operation the head losses are subtracted from the static head. Consequently, the maximum net head in pump mode is larger than the maximum net head in turbine mode. Therefore, maximum net head in pump mode is decisive for the hydraulic layout of the machine and determines the size of the pump outlet diameter of the runner.[56]

Concept of the machine	Ternary design	Reversible design
Investment costs	-	+
Space requirement	-	+
Efficiency	+	-
Installation	+	-
Switching pump/turbine	+	-
Hydraulic short circuit	+	-
High head	-	+
Operating cost	-	+
Maintenance	-	+

Table 3-6 Differences between ternary and reversible concept[57]

[56] https://neutrium.net/equipment/pump-specific-speed

[57] Stefan Höller, Helmut Jaberg, Stand der Technik von Pumpspeicheranlagen, 09/2016

Table 3-6 lists the differences between the ternary and reversible design. Compared to the three components at one shaft of the ternary design, only two components are needed at the reversible design thus lowering the investment, operation and maintenance costs. The space requirement at the ternary concept is bigger than with a pump-turbine concept although it needs a greater submergence. The efficiency of a pump-turbine has to compromise with the hydraulic design. Shorter mode change times between turbine and pump mode as well as stepless power control are possible by means of a hydraulic circuit by the ternary concept only. Figure 3-25 shows the efficiency of pump-turbines. As we have discussed before the efficiency of the complete cycle is lower than the addition of pump and turbine efficiency and can vary between 60...74 %.

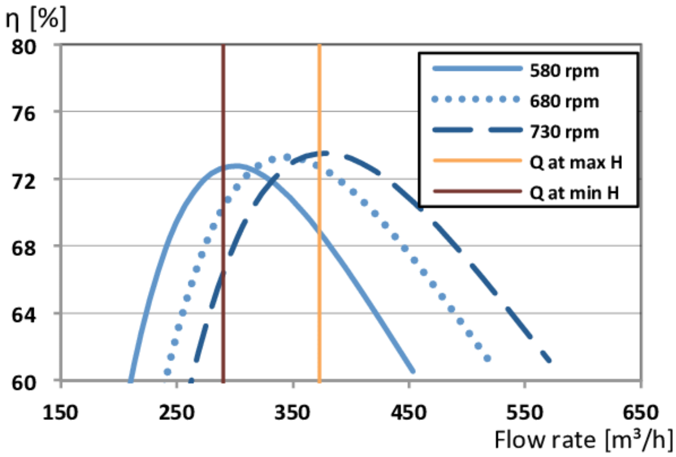


Figure 3-25 Cycle efficiency of pump-turbines[58]

[58] E.Frosina- A performance prediction method for pumps as turbines using a computational fluid dynamics , 10/2016

4. Electric machinery for hydro power plants[59,60]

The generator – turbine set converts the available hydro energy (potential or kinetic) into electric energy. The turbine transforms the hydraulic energy into work and the generator the work into electric energy. The motor – pump set consumes the electric energy. The pump is driven by a motor which is converting electric energy into work, the pump utilizes this mechanic energy to raise the potential energy of the water.

Dependent on the turbine or pump type and parameters are:

- Mechanical power input
- Shaft direction
- Hydraulic thrust
- Rated speed
- Runaway speed
- Inertia requirement

The electric parameters to be defined are:

- Voltage
- Frequency
- Power factor
- Machine inductances (reactances)
- Short circuit capability

Other parameters for instance are:

- Excitation ceiling voltage
- Variable speed range
- Range of stator or rotor frequency

The most utilized poly-phase machines are those of synchronous and asynchronous types.

The difference between the two types is that the synchronous machine rotates at a rate locked directly to the stator frequency. To contrast, the induction machine in particular with a squirrel cage rotor requires slip, the rotor must rotate slightly slower (motor mode) or higher (generator mode) than the rotating field within the air-gap in order to induce a voltage. However, the induction machine with a wound rotor can operate at synchronous speed, too. With their different capabilities, both types are used in the energy market. In the hydro-electric field synchronous machines

[59] Cf. R. Fischer -Elektrische Maschinen-Hanser 2013

[60] E.Schmidt-Elektrische Maschinen

and doubly fed induction machines directly coupled to the grid are used due to their capability to generate or absorb reactive power as required.

When we speak about variable speed concepts, we should have a look at the different frequencies. Therefore we need to compare the relation between the angular velocities or speeds, respectively.

$$\omega_S = \omega_R + \omega_m \text{ equals to } 2\pi\frac{f_1}{p} = 2\pi\frac{f_2}{p} + 2\pi n \qquad (4.01)$$

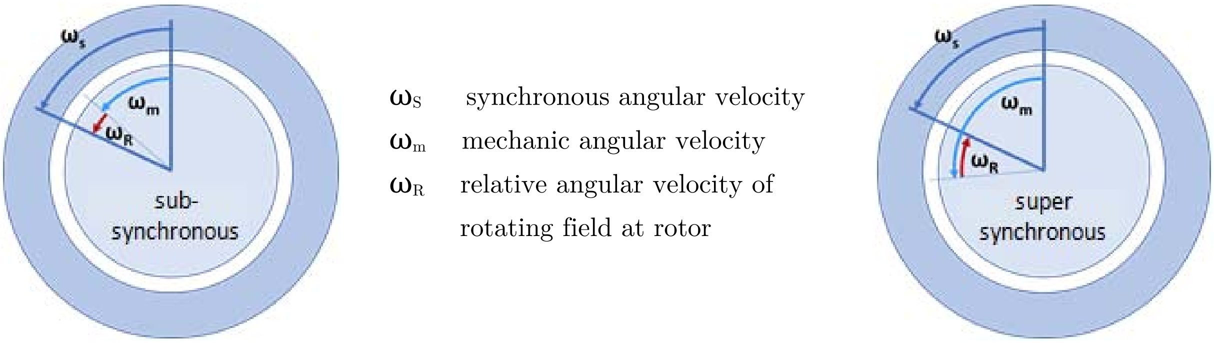


Figure 4-1 Angular velocities

where f_1 is the stator and f_2 the rotor frequency. It should be mentioned, that stator and rotor of both machine types must generate the same periodicity of the field within the air-gap, which means that there is only one number of pole(pairs) within any machine. If f_2= 0 we can consider that ω_1= ω_{mech}, this is only possible with a synchronous machine or with the doubly fed induction machine, see Table 4-1. Furthermore at f_2 bigger or smaller 0 a doubly fed induction machine (DFIM) with both generator and motor mode, and a squirrel cage induction machine either in motor or generator mode are feasible.

Frequency	Machine type/Operation mode
f_2= 0	Synchronous machine or DFIM
f_2< 0	Squirrel cage induction machine: Motor mode DFIM: Motor and generator mode
f_2> 0	Squirrel cage induction machine: Generator mode DFIM: Generator and motor mode

Table 4-1 Frequencies and its operation mode

The slip is also defined by the frequencies and is given as:

$$s = \frac{\omega_R}{\omega_S} = \frac{f_2}{f_1} \qquad (4.02)$$

4.1. Space vector theory

A simple and common way to describe a three-phase system applied on induction and synchronous machine is the space vector theory. Therein, the three-phase system is seen as a two-phase system with two equally spaced winding parts. For using the space vector theory some simplifications have to be made:

- Only the fundamental (spatial) part of physical quantities are taken into account
- Symmetrical construction of the machine in particular regarding the windings is assumed

The space vector theory has the advantage that space vectors represent the states of the electrical quantities in all the sections and describe the operating state of the machine as well. They describe both steady state and transient states, so that the formulas can be used for sudden changes, too. Before we will have a look at the space vector theory we have to reference our values:

Reference values:

$$U_{ref} = \sqrt{2} U_{nom,Str} \tag{4.3}$$

$$I_{ref} = \sqrt{2} I_{nom,Str} \tag{4.4}$$

$$\omega_{ref} = 2\pi f_N \tag{4.5}$$

$$Z_{ref} = \frac{U_{ref}}{I_{ref}} \tag{4.6}$$

$$L_{ref} = \frac{U_{ref}}{I_{ref}} \cdot \frac{1}{\omega_{ref}} \tag{4.7}$$

$$\Psi_{ref} = \frac{U_{ref}}{\omega_{ref}} \tag{4.8}$$

$$n_{ref} = \frac{\omega_{ref}}{2\pi p} \tag{4.9}$$

$$S_{ref} = \frac{3}{2} \cdot U_{ref} \cdot I_{ref} \tag{4.10}$$

Space vectors

To describe the machine, the instantaneous values of the stator currents define a stator current space vector:

$$\underline{i}_s = \frac{2}{3}(i_a + \underline{a} \cdot i_b + \underline{a}^2 \cdot i_c) \tag{4.11}$$

The phasor is defined as:

$$\underline{a} = e^{j\frac{2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \tag{4.12}$$

The complex stator voltage space vector can be setup from the stator phase voltages as:

$$\underline{u}_s = \frac{2}{3}(u_a + \underline{a} \cdot u_b + \underline{a}^2 \cdot u_c) \tag{4.13}$$

The space vector of the stator linkage flux is defined as:

$$\underline{\Psi}_s = \frac{2}{3}(\Psi_a + \underline{a} \cdot \Psi_b + \underline{a}^2 \cdot \Psi_c) \tag{4.14}$$

Basically, we differentiate between three coordinate systems to describe rotating machines:

- the stator fixed reference frame (α-β) is connected to the stator winding
- the rotor fixed reference frame (d-q) is connected to the rotor winding
- the flux orientated reference frame (x-y) is orientated to the direction of the flux space vector of either stator or rotor

A current space vector can be expressed in the α-β coordinate systems as:

$$\underline{i}_{\alpha,\beta} = i \cdot e^{j\alpha_S}, \tag{4.15}$$

or in the d-q rotor coordinate system, thereby the d-q coordinate system rotates with the angular shift of α_R:

$$\underline{i}_{d,q} = i \cdot e^{j\alpha_R}, \tag{4.16}$$

and the third way to express a current space vector is the x-y coordinate system, it rotates with an angular shift α_K, respectively:

$$\underline{i}_{x,y} = i \cdot e^{j\alpha_K}. \tag{4.17}$$

Depending on the task, the choice of the coordinate system can vary and a coordinate system transformation:

$$\underline{i}_{d,q} = \underline{i}_{\alpha,\beta} \cdot e^{-j\gamma_m}, \tag{4.18}$$

$$\underline{i}_{x,y} = \underline{i}_{\alpha,\beta} \cdot e^{-j\gamma_K} \tag{4.19}$$

will be required.

The angular velocities are defined as:

$$\omega_m = \frac{d\gamma_m}{d\tau}\,, \tag{4.20}$$

$$\omega_K = \frac{d\gamma_K}{d\tau}\,. \tag{4.21}$$

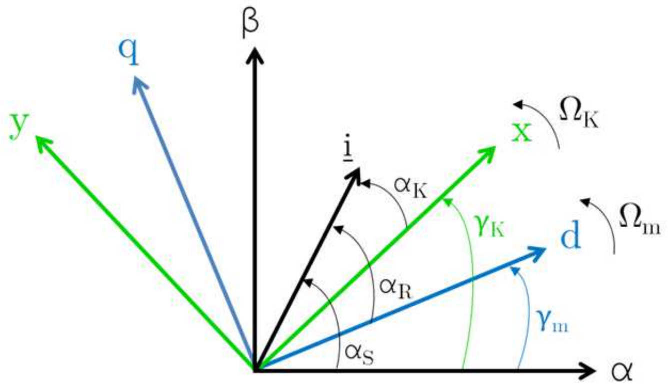


Figure 4-2 Space vector diagram for the different coordinate systems

The space vectors of the stator and rotor linkage flux in respect to an identical coordinate system are combined to the following equations:

$$\underline{\Psi}_S = l_S \cdot \underline{i}_S + l_h \cdot \underline{i}_R, \tag{4.22}$$

$$\underline{\Psi}_R = l_h \cdot \underline{i}_S + l_R \cdot \underline{i}_R \tag{4.23}$$

Therein l_S, l_R ,l_h denote stator, rotor and magnetising inductances.

Voltage equation of the stator winding with regard to the flux orientated coordinate system:

$$\underline{u}_S = r_S \cdot \underline{i}_S + \frac{d\underline{\Psi}_S}{d\tau} + j \cdot \omega_K \cdot \underline{\Psi}_S \tag{4.24}$$

Voltage equation of rotor winding with regard to the flux orientated coordinate system:

$$\underline{u}_R = r_R \cdot \underline{i}_R + \frac{d\underline{\Psi}_R}{d\tau} + \mathrm{j} \cdot (\omega_K - \omega_m) \cdot \underline{\Psi}_R \tag{4.25}$$

Finally we can evaluate the electromagnetic torque from:

$$t_i = -\mathrm{Im}(\underline{i}_S^* \cdot \underline{\Psi}_S) \tag{4.26}$$

independently from the used coordinate system.

Figure 4-3 shows the torque, its total amount is represented by the blue square, which is the area between nominal vector i_S and ψ.

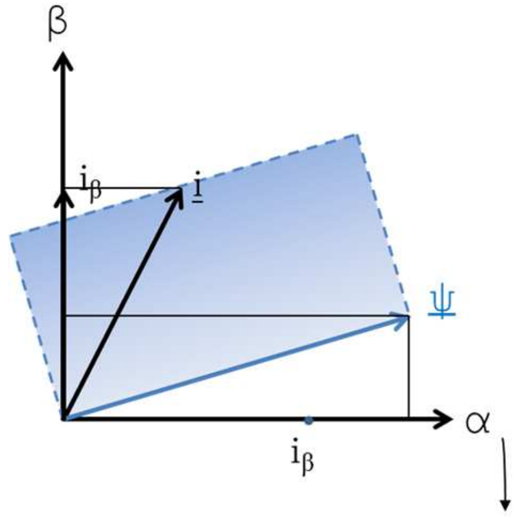


Figure 4-3 Torque of the induction machine

4.2. Asynchronous (induction) machine

The asynchronous machine is the mostly used electric machine nowadays. It rotates, like its name is already indicating, asynchronous to the frequency of the stator. This means that the rotor is retarding the rotating field during motor operation and is leading in generator mode by such an amount to sufficiently produce the required torque. The asynchronous machine has both one resistance and leakage reactance on the primary and on the secondary side as well as a main reactance representing the magnetic coupling over the air gap, see Figure 4-4. Thereby, the parameter with 1 symbolised the stator and 2 the rotor side.

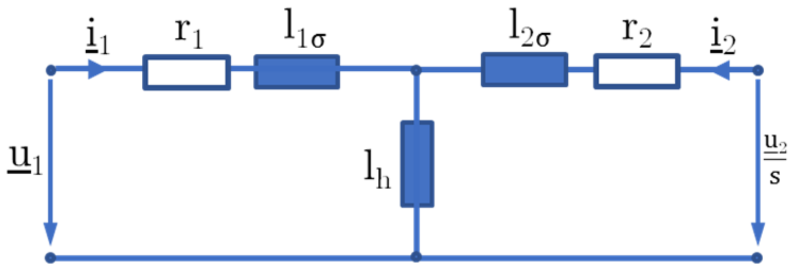


Figure 4-4 Equivalent circuit of an asynchronous machine

The construction of the stator for any induction motor is almost the same. But the rotor construction differs with respect to the two types

- Squirrel cage asynchronous machine
- Slip ring asynchronous machine

Stator:

The stator is the outer most component of the machine. It is almost the same for any given asynchronous machine. It is made up of a number of stampings, which are slotted to receive the windings. The three phase winding is placed into the slots of the laminated core and the phase windings are electrically spaced 120 degrees apart. These windings are connected as either star or delta depending upon the requirement. The leads are taken out usually three in number brought out to the terminal box mounted on the machine frame.[61]

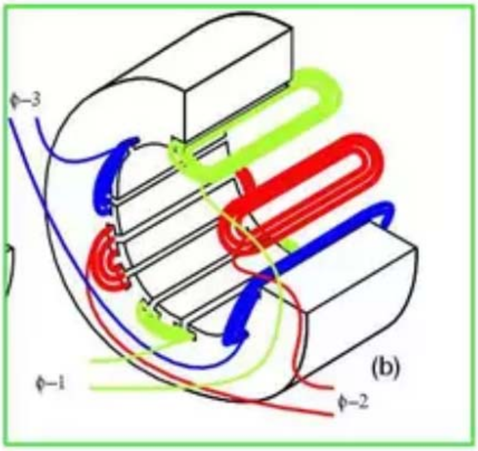


Figure 4-5 Stator of an asynchronous machine[62]

4.2.1. Squirrel cage induction machine

The stator of a squirrel cage induction has already been mentioned instead the rotor of the machine is different. Figure 4-6 shows the equivalent circuit of a squirrel cage induction machine. The circuit is closed with a resistance, which is depending on the slip.

[61] Cf. https://www.brighthubengineering.com/diy-electronics-devices/43723-how-are-squirrel-cage-induction-motors-constructed/
[62] https://www.brighthubengineering.com/diy-electronics-devices/43723-how-are-squirrel-cage-induction-motors-constructed/

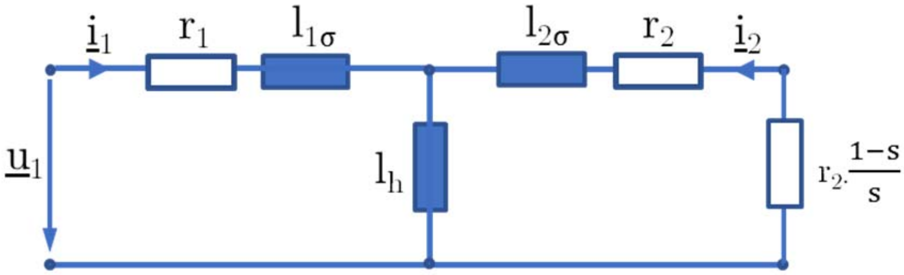


Figure 4-6 Equivalent circuit of a squirrel cage machine

Total referenced admittance y_1 considering variable speed respectively frequency without slip of the equivalent circuit with the load $r_2 \cdot \omega_S/\omega_R$ is:

$$y_1 = \frac{r_2 + j\omega_2 l_2}{r_1 r_2 - \sigma\omega_1 l_1 \omega_2 l_2 + j(r_2\omega_1 l_1 + r_1\omega_2 l_2)} \tag{4.27}$$

while the air gap power can be deduced from:

$$p_D = \mathrm{Re}(y_1^* u_1^* u_1 - y_1^* u_1^* y_1 u_1 r_1) \tag{4.28}$$

Calculating the frequency of the rotor breakdown ω_{2K} considering r_1 decrements to 0 with the stray filed coefficient

$$\sigma = 1 - \frac{l_h^2}{l_1 l_2} \tag{4.29}$$

results in:

$$\omega_{2K} = \pm\frac{r_2}{\sigma l_2} \tag{4.30}$$

Hence, air-gap power as well as ratio of air-gap power and breakdown power result from

$$p_D = u_1^2 \frac{(1-\sigma) r_2 \omega_1 l_1 \omega_2 l_2}{(\sigma\omega_1 l_1 \omega_2 l_2)^2 + (r_2\omega_1 l_1)^2} \qquad \frac{p_D}{p_{DK}} = \frac{2}{\frac{\omega_2}{\omega_{2K}} + \frac{\omega_{2K}}{\omega_2}} \tag{4.31}$$

In case the stator resistance is not equal 0, the frequency of the rotor breakdown can be expressed as:

$$\omega_{2K} = \pm\frac{r_2}{l_2}\sqrt{\frac{r_1^2 + (\omega_1 l_1)^2}{r_1^2 + (\sigma\omega_1 l_1)^2}} = \pm\frac{r_2}{l_2}\sqrt{K} \tag{4.32}$$

Now performing the calculation based on variable speed including the slip and $r_1 \neq 0$, thus ratio of air-gap power and breakdown power result as:

$$\frac{p_D}{p_{DK}} = 2\sigma \frac{r_2(\omega_1 l_1)^2 \omega_2 l_2}{(r_1 r_2 - \sigma\omega_1 l_1 \omega_2 l_2)^2 + (r_2\omega_1 l_1 + r_1\omega_2 l_2)^2} \tag{4.33}$$

Or with r_2 expressend with the frequencyy of breakdown to:

$$\frac{p_D}{p_{DK}} = 2\sigma \frac{\omega_{2K}\omega_2\sqrt{K}}{(\omega_{2K}^2 + \omega_2^2)\left((\frac{r_1}{\omega_1 l_1})^2 + \sigma^2\right) + 2\frac{r_1}{\omega_1 l_1}(1-\sigma)\omega_2\omega_{2K}\sqrt{K}} \tag{4.34}$$

Consequently, without considering the stator resistance, the break-down rotor frequency is a constant. Algo, the dependency of the air-gap power is only related to the rotor frequency.

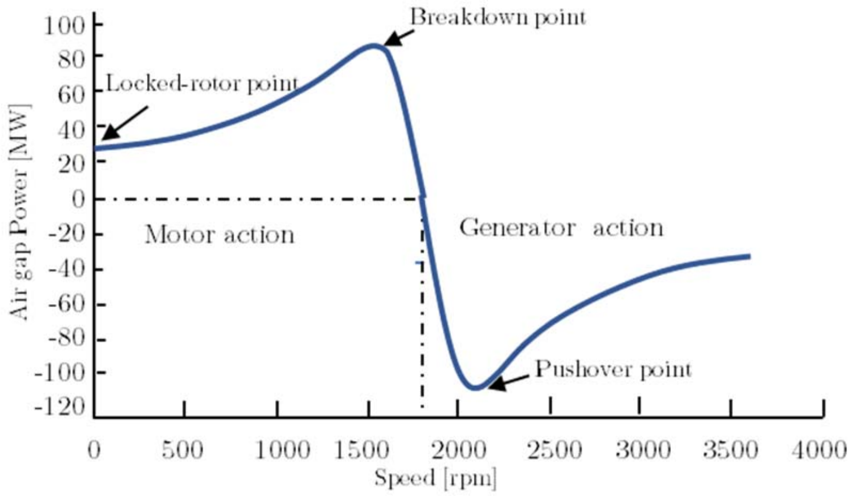


Figure 4-7 Air-gap power vs. speed

The torque/speed characteristic shows two characteristic torque values. The maximum value of the torque in the motor region is called the breakdown torque, while the maximum of the torque in the generator region is called the pushover torque. Accelerating the rotor either beyond the rotor frequency of breakdown or above the rotor frequency of the pushover brings the machine into instable operating areas.

The squirrel cage rotor:

This kind of rotor usually consists of a cylindrical laminated core with parallel slots for carrying the rotor bars of copper or aluminium or its alloys. Here the rotor core is laminated to avoid power losses from eddy currents and hysteresis. The conductor bars are inserted from one end of the rotor and one bar in each slot. There are end rings which are welded or electrically braced or even bolted at both ends of the rotor, thus maintaining electrical continuity. These end rings are short-circuited, giving them a beautiful look similar to a squirrel cage where the name is derived of. For grid connected machines, the rotor bars are usually skewed to reduce or even eliminate the slot harmonics. However, when connected to an inverter there is usually no skewing of the rotor bars.

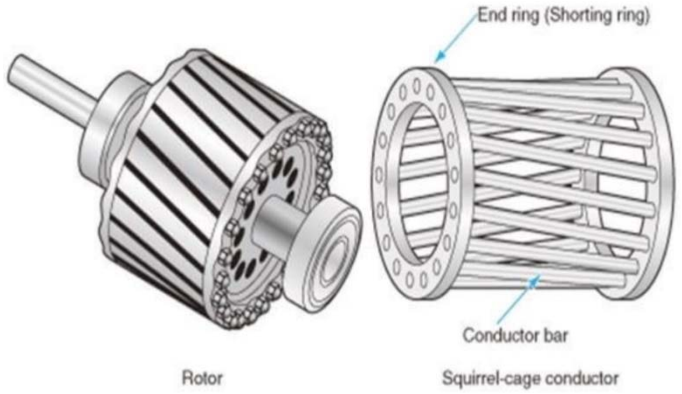


Figure 4-8 Rotor winding of a squirrel cage machine[61]

4.2.2. Slip ring machines[63]

Slip ring induction machines consist of a three-phase winding on the rotor where slip rings are connected with each phase winding. The slip ring induction motor is also known as wound rotor induction motor. Figure 4-9 presents the equivalent circuit diagram of the slip ring machine. Based on the indicated reference system of the circuit we can see that the real part can be either positive or negative whereas the imaginary part of the rotor impedance is mostly negative, which means that active power can be fed-in or consumed while the reactive power will always be fed-in (see Table 4-2).

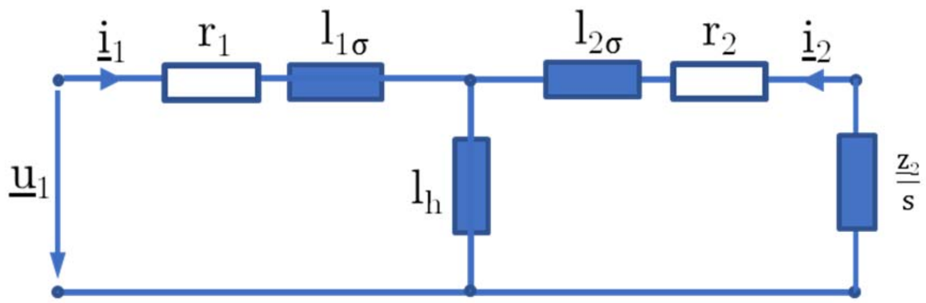


Figure 4-9 Equivalent circuit of a slip ring machine

Slip ring machine impedance		
$Re(z_2) < 0$	$Im(z_2) < 0$	Super-synchronous motor mode
$Re(z_2) < 0$	$Im(z_2) < 0$	Sub-synchronous generator mode
$Re(z_2) > 0$	$Im(z_2) < 0$	Sub-synchronous motor mode
$Re(z_2) > 0$	$Im(z_2) < 0$	Super-synchronous generator mode

Table 4-2 Slip ring machine - equivalent rotor impedance

[63] Cf. A. Binder: Elektrische Maschinen &Antriebe- Viewegs- 08/2007

Over the last decade, slip ring machines were only used in special drive applications. With the development of power electronics, they were used more and more with variable speed drives. Thereby, the rotor windings are connected through slip rings to an inverter. Details will be discussed in the chapter of variable speed.

As we have seen before, the stator design for the slip ring machine is practically the same as for the squirrel cage machine; however, the rotor design is completely different. The rotor of a slip ring induction motor is made of cylindrical laminated core with parallel slots for carrying the rotor conductors of the three-phase rotor winding. This winding is either star or delta connected; the ends of the phase windings are connected to the slip rings. The rotor has a number of slip rings according to the number of phases, which are mounted on the shaft but insulated from the shaft, each one equipped with brushes. In very special cases the neutral lead is brought out via an additional slip ring, too.

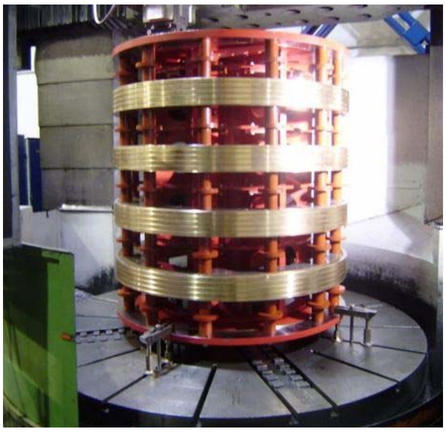


Figure 4-10 DFIM sliprings of Goldisthal[64]

4.3. Synchronous machines[65]

Synchronous machines are used mainly as generators however for specific drive applications synchronous motors are used, too. In contrary to induction machines, synchronous machines rotate synchronously to the frequency of the stator current. With the machine operating under load both magneto motive forces of stator and rotor windings are opening up a torque depending angle, the so called load angle.

As already mentioned, it is a simply and common way to describe a synchronous machine by means of the space vector theory. Figure 4-11 shows a synchronous machine which consists of the excitation field winding (f), the damper windings (D,Q) and the stator windings (d,q).

[64] Andritz Hydro- Pumped Storage Hydro Power Plant Goldisthal,07/17

[65] Cf. A. Binder: Elektrische Maschinen &Antriebe- Viewegs- 08/2007

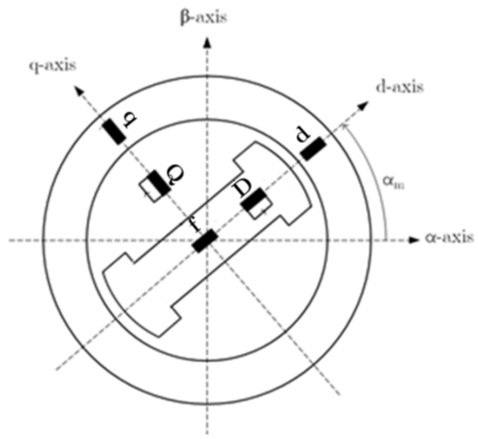


Figure 4-11 Synchronous machine in d and q-axis[63]

Construction wise we differentiate between two types of synchronous machines:

1. Synchronous machines of non-salient pole type (with cylindrical rotor design and distributed rotor winding)
2. Synchronous machines of salient pole type

4.3.1. Steady state equivalent circuits and powers

Since the DC-excited field winding will be orientated always along the d-axis, with regard to the d-q coordinate system, we have to setup different equivalent circuits for the two kinds of synchronous machines used in hydro power plants.

Decomposing the stator voltage into the rotating d and q coordinate system leads to:

$$u_d = r_s i_d + \frac{\mathrm{d}\,\Psi_d}{\mathrm{d}\tau} - \omega_m \Psi_q, \tag{4.35}$$

$$u_q = r_s i_q + \frac{\mathrm{d}\,\Psi_q}{\mathrm{d}\tau} + \omega_m \Psi_d \tag{4.36}$$

Therein, the linkage flux equations are as follow:

$$\Psi_d = l_d i_d + l_{df} i_f, \tag{4.37}$$

$$\Psi_q = l_q i_q \tag{4.38}$$

Consequently, the equivalent circuits of the non-salient pole synchronous machine are shown Figure 4-12, therein i_μ denotes the magnetising current.

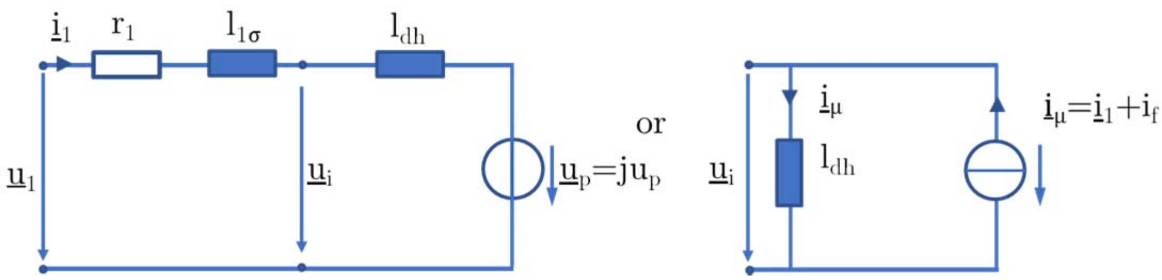


Figure 4-12 Equivalent circuit of the non-salient pole machine

The equivalent circuits of the salient pole synchronous machine are shown in Figure 4-13.

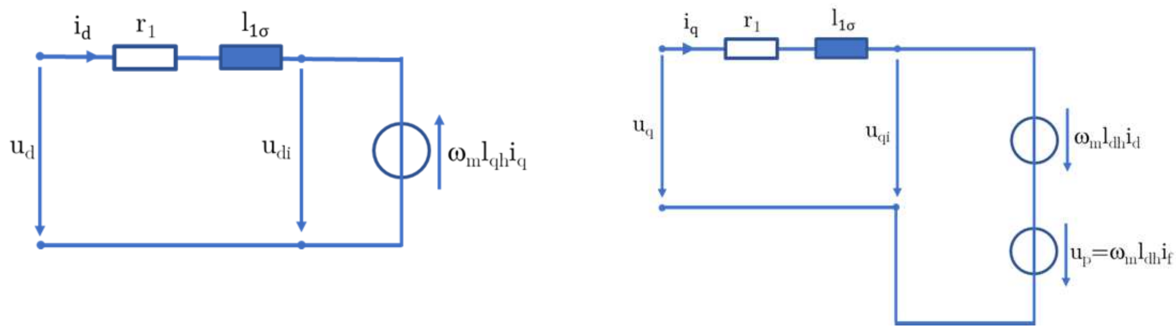


Figure 4-13 Equivalent circuit of the salient pole machine in d/q-axis

The expressions below demonstrate the dependence of the active power on the load angle δ as well as on the excitation voltage u_P, the stator voltage u_S, the synchronous reactance l_d, and quadrature axis reactance l_q.

For the non-salient pole machine the active and reactive power results as:

$$p_S = +\mathrm{Re}(\underline{i}_S^* \underline{u}_S) = \frac{u_S u_P}{\omega_S l_d} \sin(\delta) \tag{4.39}$$

$$q_S = +\mathrm{Im}(\underline{i}_S^* \underline{u}_S) = \frac{u_S (u_S - u_P \cos(\delta))}{\omega_S l_d} \tag{4.40}$$

The active and reactive power of a salient pole machine are given as following:

$$p_S = +\mathrm{Re}(\underline{i}_S^* \underline{u}_S) = \underbrace{\frac{u_S u_P}{\omega_S l_d}}_{\text{cylindrical part}} \sin(\delta) + \underbrace{\frac{u_S^2}{2\omega_S} (\frac{1}{l_q} - \frac{1}{l_d}) \sin(2\delta)}_{\text{salient pole part}} \tag{4.41}$$

$$q_S = +\mathrm{Im}(\underline{i}_S^* \underline{u}_S) = \underbrace{\frac{u_S (u_S - u_P \cos(\delta))}{\omega_S l_d}}_{\text{cylindrical part}} + \underbrace{\frac{u_S^2}{2\ \omega_S} (\frac{1}{l_q} - \frac{1}{l_d})(1 - \cos(2\delta))}_{\text{salient pole part}} \tag{4.42}$$

Figure 4-14 and Figure 4-15 show the maximum power respectively torque depending on the load angle and the excitation current of a non-salient and salient pole synchronous machine (P_K represents the maximum static torque before slipping).

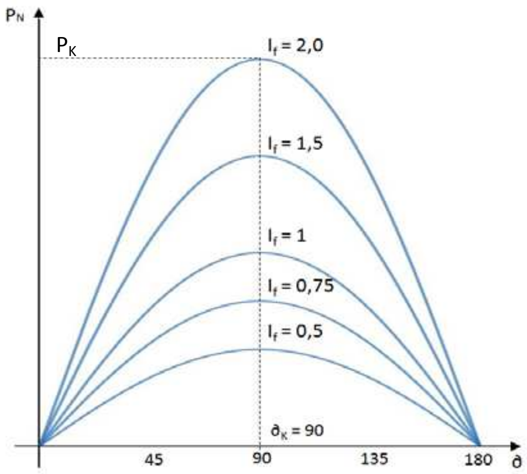


Figure 4-14 Torque - load angle characteristics of a non-salient pole machine[65]

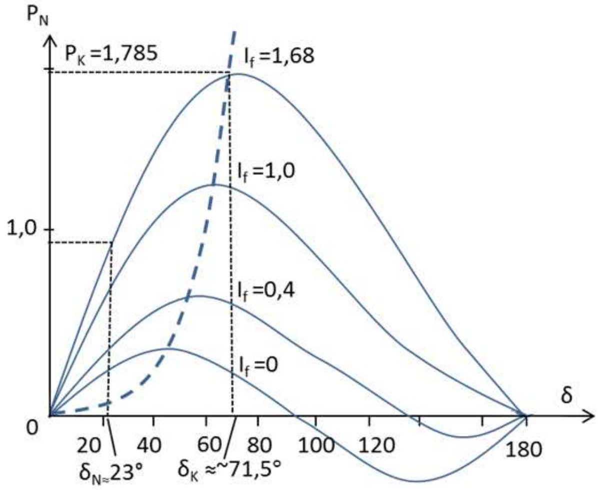


Figure 4-15 Torque - load angle characteristics of a salient pole machine[66]

4.3.2. Transient equivalent circuits

The steady state linkage fluxes of stator, damper and excitation field windings are now modified according to:

$$\Psi_d = l_d i_d + l_{dD} i_D + l_{df} i_f, \tag{4.43}$$

$$\Psi_q = l_q i_q + l_{qQ} i_Q, \tag{4.44}$$

$$\Psi_D = l_D i_D + l_{dD} i_d + l_{Df} i_f, \tag{4.45}$$

$$\Psi_Q = l_Q i_Q + l_{qQ} i_q, \tag{4.46}$$

$$\Psi_f = l_f i_f + l_{Df} i_D + l_{df} i_d. \tag{4.47}$$

Figure 4-16 shows the classical equivalent circuit diagrams for a synchronous machine for the transient synchronous reactance $l_{d'}$, sub-transient quadrature axis reactance $l_{q''}$ and the sub-transient synchronous reactance $l_{d''}$ assuming that the main reactance in d-axis l_{dh} is the same for all three windings (stator, rotor and damper). Instead Figure 4-17 presents the modified equivalent with a magnetic coupling bigger between D/f against D/d or f/d windings. Nevertheless, is it possible to reconfigure the classical equation circuits with:

[66] B. Aschendorf- Elektrische Maschinen,2008

$$l_{f\sigma} = l_{2\sigma} + l_{f\sigma}{}^{*} \tag{4.48}$$

$$l_{Q\sigma} = l_{2\sigma} + l_{Q\sigma}{}^{*} \tag{4.49}$$

$$l_{D\sigma} = l_{f\sigma} \frac{l_{2\sigma} l_{Q\sigma}{}^{*} + l_{f\sigma} l_{D\sigma}{}^{*}}{l_{f\sigma}{*}^{2}} \tag{4.50}$$

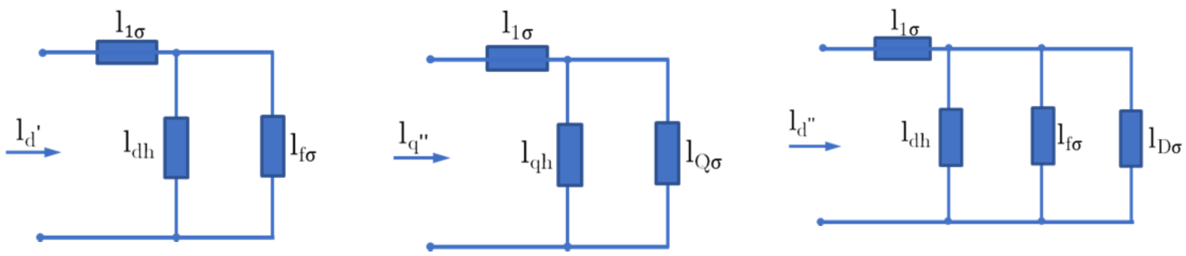


Figure 4-16 Classical equivalent circuit diagram

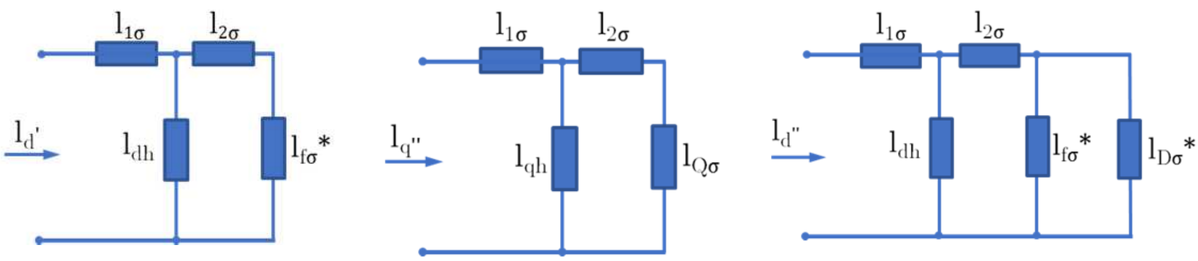


Figure 4-17 Modified equivalent circuit diagram

4.3.3. Non-salient pole synchronous machine

Non-salient rotors - also known as cylindrical rotors - are used mostly for high-speed machines but also with a number of poles up to twelve.

In this type of rotor, Figure 4-19, the excitation current flows through a distributed rotor winding. Cylindrical rotors with two or four poles are made from solid forgings of high-grade nickel chrome molybdenum steel. Rotors with a higher number of poles consist of thicker laminations welded to a shaft. The ratio of rotor length l divided by the pole pitch τ_p is decisive for the design of an electrical machine. Due to the rather low number of poles, a significantly larger air gap, the rotor of such machines has comparatively small diameters and large axial lengths.

The construction with two or four poles, provides a greater mechanical strength and permits more accurate dynamic balancing. The smooth rotor of the machine causes less windage losses and operation is less noisy because of the uniform air-gap. The structural design of the wound rotor synchronous machine compared to a salient pole synchronous machine is different only on the rotor side. All the static components such as stator core, stator frame, stator winding, bearings, bearing bracket etc. are for both of the same design concept. Supply with DC current is performed by means of slip rings and brushes or via a brushless exciter with rotating rectifiers. However, the rotor winding for non-salient pole machines consists of distributed concentric pole windings embedded in slots over the circumference of the rotor in order to establish the same effect of flux as a salient pole. Due to the concentricity of the winding rather large winding overhangs are the consequence which requires proper fixation and support against the centrifugal forces, quite similar as discussed at DFIM.

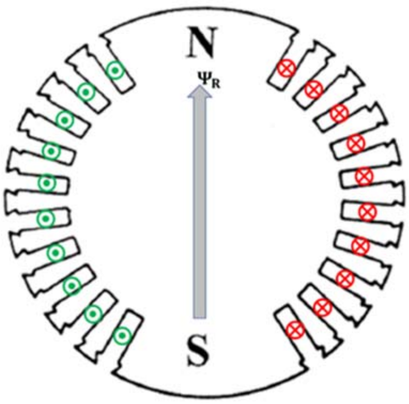


Figure 4-18 Rotor section with slots for two pole machine $q_2=5$

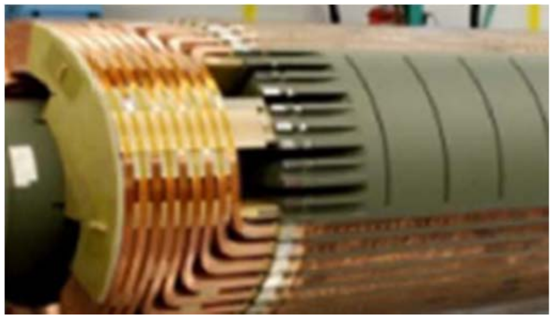


Figure 4-19 Rotor winding of a two pole turbo generator[67]

4.3.4. Salient pole machine with concentrated pole windings[68]

The stator consists of the stator frame welded of steel sheets which protects and supports the inner part of the machine namely the stator core and winding. The stator core is made of laminations of silicon steel material. Its function is to provide an easy path for the magnetic flux and to accommodate the stator winding. Slots are cut on the inner periphery of the stator core in which mostly a three-phase winding is inserted. The winding is made either of Roebel bars or coils consisting of a number of enamelled rectangular copper conductors. The main insulation of the winding consists of mica tapes impregnated with epoxy resin and then hardened in an oven. The bars or coils of each phase are embedded and fixed in the slots by means of wedges. When the current flows in a distributed winding it produces a more or less sinusoidal space distribution of magneto motive force. Usually the winding is star connected, directly connected to the electric system and hence the rotational speed is strictly fixed by the frequency of the electric system and the number of poles.

Salient pole means that the rotor is fitted with poles projecting out from the surface of the rotor core, the rotor hub or rotor rim. Since the rotor poles are subject to

[67] A. Binder: Elektrische Maschinen &Antriebe- Viewegs- 08/2007

[68] Cf. R. Fischer -Elektrische Maschinen-Hanser 2013

changing magnetic fields caused by the higher harmonics in the air-gap, it is made of steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled in stacking laminations to the required length. A salient pole synchronous machine has a non-uniform air-gap. The air-gap minimum is under the pole center and its maximum is in between the poles. The rotors are constructed for medium and low speeds as they have a larger number of poles. As already mentioned, the length of the rotor l divided by the pole pitch τ_p is decisive for the design of an electrical machine. Because the ratio is smaller compared to a cylindrical rotor machine the consequence are larger diameters and shorter axial core length. The salient pole rotor consists of the following important parts.

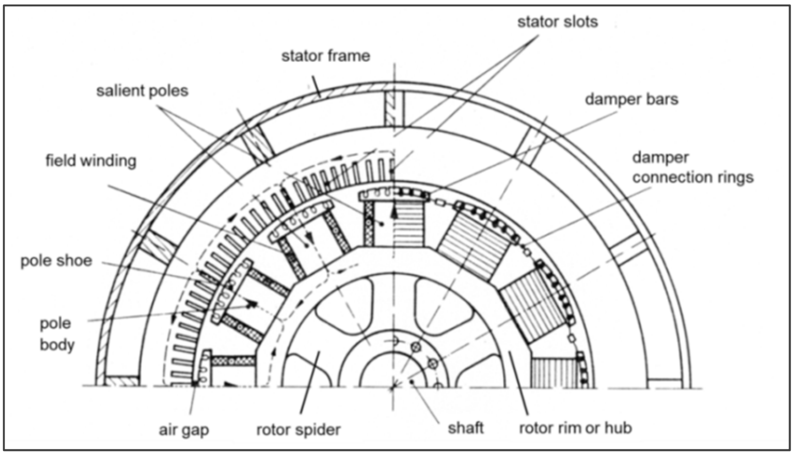


Figure 4-20 Section of a synchronous machine[69]

The spider is made of cast iron or welded of steel sheets. It is keyed to the shaft. To provide an easy path for the magnetic flux for low speed application a laminated rim is mounted on it, for high speed application a massive yoke is shrunk onto the shaft and/or spider in order to withstand the centrifugal forces during operation. At the outer surface the poles are keyed to it. The poles are made of laminated sheet steel material bolted together between rigid pressure plates. Rim and pole provide the least reluctance path for the magnetic field and the pole with its shoe distributes the field over the whole periphery producing a sinusoidal wave.

The field winding, pole winding or exciting winding is wound on edge and then placed around the pole body. Supply with DC current is performed by means of slip rings and brushes or via a brushless exciter with rotating rectifiers. When direct current flows through the field winding the rotor winding is producing the required magnetic field to excite the machine. Depending on the rotor current the machine is able to even over compensate the needed reactive power. The rotor winding, through which direct current flows, generates the excitation field, which rotates with synchronous speed.

[69] Cf.H. Kleinrath-Grundlagen elektrischer Maschinen-Akademische Verlagsgeschellschaft- 1975

At the outermost periphery – in the pole shoe - holes are provided in which copper bars are inserted and short-circuited at both sides by rings forming the damper winding.

4.3.5. Permanent magnet synchronous machine (PMSM)[68]

A permanent magnet synchronous machine has a higher efficiency than other types of synchronous machines, as the excitation is provided without any energy supply by poles consisting of permanent magnets. However, the materials used for producing permanent magnets are expensive, and the poles are difficult to be handled during manufacturing.

Because of the permanent magnets we do not need an excitation winding anymore. The excitation field will be provided by the permanent magnets, thus we can assume constant field current as of:

$$\Psi_{PM} = l_{dh} \cdot i_{f0} = constant \tag{4.51}$$

in order to describe permanent magnet machines with the former mentioned equivalent circuits Figure 4-12 and Figure 4-13.

Additionally, we have to use the modified linkage fluxes according to:

$$\Psi_d = l_d i_d + l_{dh} i_D + \Psi_{PM}, \tag{4.52}$$

$$\Psi_D = l_D i_D + l_{dh} i_d + \Psi_{PM,D} \tag{4.53}$$

PSM applications are found nowadays in the small respectively compact hydro field up to approximately 10 MVA.

Components and design are as described before, but only the poles are made of permanent magnets. Consequently no field winding, excitation, slip rings, brushes, etc. is required, thus being a cost-effective solution for small hydro.

The permanent magnets can be mounted on the surface of the rotor or buried into the yoke. The designs are shown in Figure 4-21 and Figure 4-22. Synchronous machines with surface permanent magnets are glued and fixed onto the rotor with a bandage. Pressing or shrinking the bandage of the rotor creates a contact pressure and tangential pretension. Instead at buried permanent magnet machines are held by the rotor plate, and compared to the surface mounted magnets no bandages and less magnetic material is needed due to space-saving design. Nevertheless buried magnets have a leakage flux and this causes more total losses.[70]

[70] A. Binder- PM-Rotoren mit Oberflächen und vergrabenen Magneten, Technische Universität Darmstadt

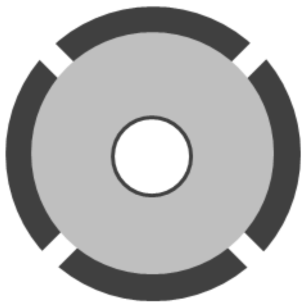


Figure 4-21 Surface mounted permanent magnets[71]

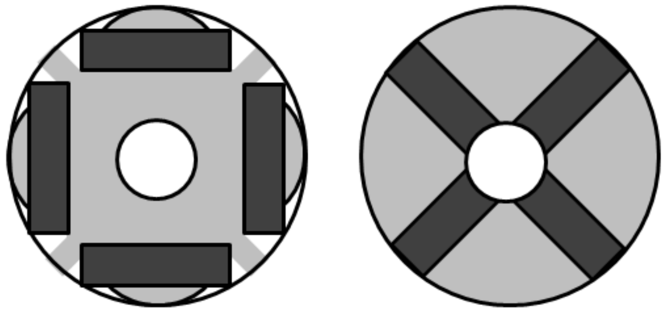


Figure 4-22 Buried permanent magnets tangential (left) and radial arrangement (right)[71]

Hydro power applications basically are using salient pole type machines or for smaller size with low inertia requirements non-salient pole machines or surface mounted permanent magnet machines used as start-ups units. In the table below a comparison of the three construction types is shown.

The major differences between salient, non-salient pole and permanent machines are:

	Salient poles	Non-salient poles	Permanent magnet
Inertia	high	low	high
Synchronous reactance xd	approx. 1	>1,3	approx. 1
Quadrature reactance xq	(0,6...0,7)xd	approx. xd	xq ~ xd
Transient reactance xd'	(0,3...0,4)	higher than salient	approx. xd
Sub-trans. reactance xd"	(0,10...0,15)	lower than salient	higher than non-salient
Excitation current		higher than salient	n.a.
Air-gap	smallest in pole center	constant	smallest in pole center

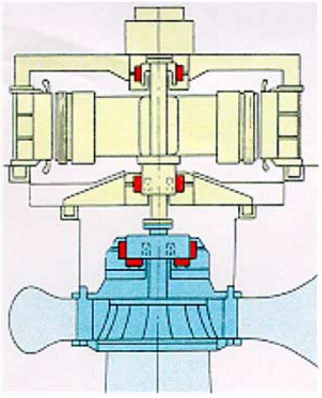
Table 4-3 Comparison of salient / non salient pole / permanent magnet synchronous machines[68]

[71] https://images.app.goo.gl/pUYc3w58pJKvZEvUA

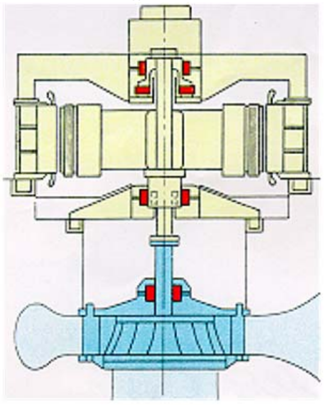
4.4. Generator construction

Due to the wide range of output and speed and turbine types and axis orientation a number of construction types have been developed. Below is a summary of the mostly used ones.

mostly for high mechanical speed units

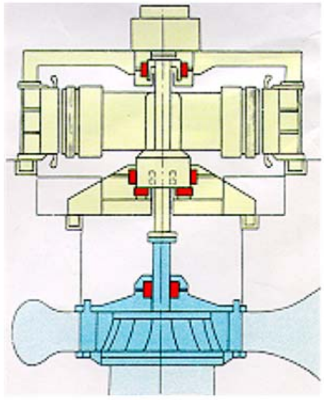


W3/ IM 8025	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	/	1
Guide bearings	2	1



W3/ IM 8426	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	1(above)	/
Guide bearings	2	1

medium speed units



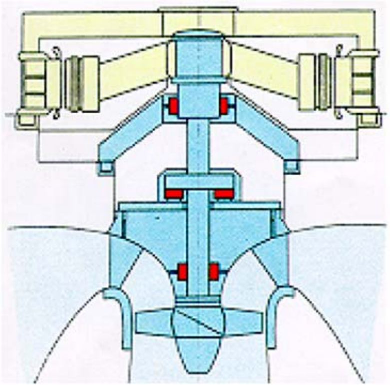
W3/ IM 8226	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	1(below)	/
Guide bearings	2	1

Figure 4-23 Generation unit construction types[72]

The colour code indicates the limits of supply. “Blue” is scope of the turbine supplier, whereas “yellow” is within scope of the generator supplier, some of the types of construction are in principal equal and differ only in the supply responsibility.

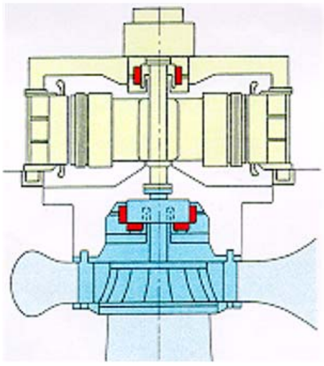
[72] Andritz Hydro: HYDRO GENERATORS-10/2009

Low speed units



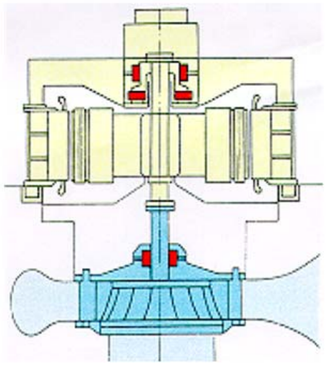
W6/ IM 8141	Generator supply	Turbine supply
Shaft	/	Through going shaft
Thrust bearings	/	1
Guide bearings	/	2

smaller units



W1/ IM 8016	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	/	1
Guide bearings	1	1

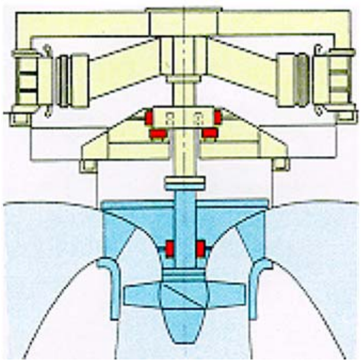
smaller units



W21/ IM 8416	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	1(above)	/
Guide bearings	1	1

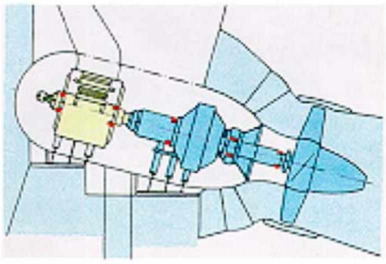
Figure 4-24 Generation unit construction types[72]

Low speed units



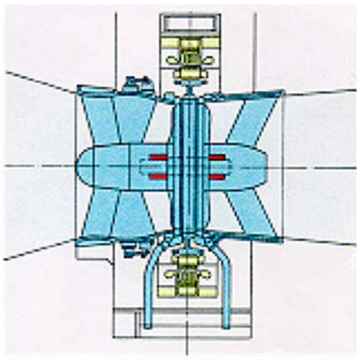
W3/ IM 8206	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	1(below)	/
Guide bearings	1	1

pit type units



A2/ IM 5410	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	/	1
Guide bearings	2	3

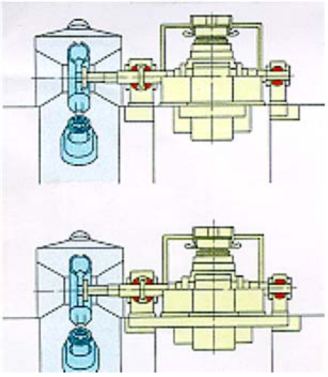
STRAFLO units



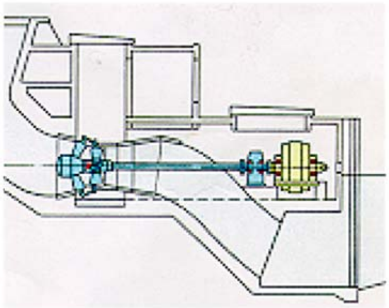
A2/ IM 5410	Generator supply	Turbine supply
Shaft	/	Through going shaft
Thrust bearings	/	1
Guide bearings	/	2

Figure 4-25 Generation unit construction types[72]

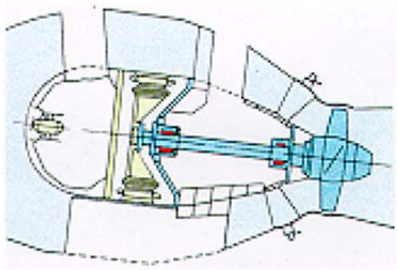
horizontal unit
with pedestal bearings



S-type unit



bulb type unit



D6/12 IM 7215/7255	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	If necessary	/
Guide bearings	2	/

D6/12 B3	Generator supply	Turbine supply
Shaft	Flanged shaft	Flanged shaft
Thrust bearings	/	1
Guide bearings	2	3

A2/ IM 5410	Generator supply	Turbine supply
Shaft	/	Through going shaft
Thrust bearings	/	1
Guide bearings	/	2

Figure 4-26 Generation unit construction types[72]

5. Why variable speed generation?

Pumped storage power plants with fixed speed operation have limits by responding to grid changes and for quickly changing requirements. A common concept, the pumped storage power plant is the reversible design. Configured with a pump-turbine, it acts as a turbine in one direction and as a pump in the other with a motor/generator. This concept works sufficient, but it also has its limitations

5.1. Variable speed introduction[73]

Conventional pumped storage power plants usually are operated at fixed speed. Therefore, optimised equipment for a wide operating range is needed. Fixed speed units generate grid frequency with a defined number of poles. At fixed speed operation, when the hydraulic parameters are changing, the turbine's efficiency is not at its best point. Running the unit at different speeds, the turbine can be operated more often at the optimum efficiency point for the actual hydraulic parameters. In the past, without the semiconductor technology, primarily mechanical solutions were developed to vary speed. One option was to design a synchronous machine which is equipped with a changeable number of poles, meaning the machine was able to operate at two synchronous speeds. With the development of the power electronics technology for large currents and higher voltages, other options of frequency conversion, namely variable speed operations, were developed. The different operational speeds are shown in Table 5-1.

Speed forms	Fixed speed	Dual speed	Variable speed
Type	$n = \frac{f_1}{p}$	$n_1 = \frac{f_1}{p_1}$ $n_2 = \frac{f_1}{p_2}$	$n = \frac{(f_1 \pm f_2)}{p}$

Table 5-1 Speed formulars[73]

In Figure 5-1 three different speed operation modes are shown. Fixed speed operation may have some limitations because of significant efficiency drops resulting from big head variation. Compared to the fixed speed machines with dual speed due to two different number of pairs shows a better efficiency at low heads. Furthermore, variable speed allows good efficiencies for large head variations.[74]

[73] Cf. Andritz Hydro-Why variable speed, 01/2018

[74] European Hydropower Generation and Pumped Storage Forum- Reviewing the Latest Technical Developments of Hydro Technology for Improved Performance Variable Speed- 01/2012

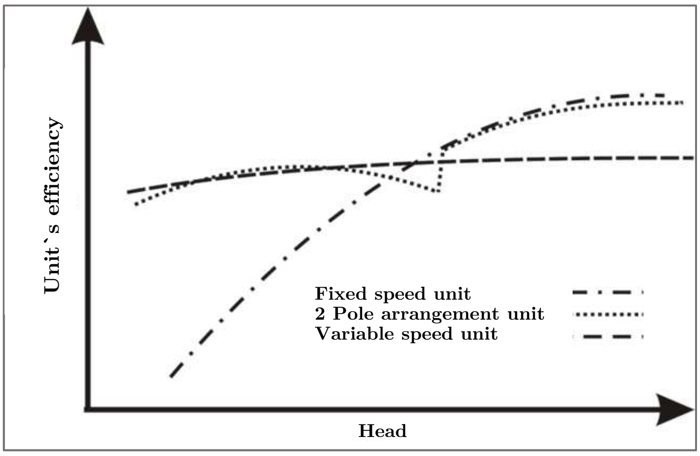


Figure 5-1 Efficiency line for different speed operations[75]

Variable speed permits a more dynamical adjustment of the power due to the flywheel effect. For fixed speed operation, the power adjustment of conventional synchronous machines can only be made by adjusting the discharge by changing of the wicket gates opening. The wicket gate movement is also the only possibility to influence load variations, resulting in a long response time due to the large time constants of the hydraulic system. During dynamic grid operation it is necessary to inject to or absorb active power from the grid within a short reaction time. With this measure, the grid can be stabilized after system disturbances. Variable speed units are able to react to such disturbances by adapting the speed to the new power requirements and compensate (absorb or release) the energy in the inertia of the hydraulic system. This instantaneous response of the active power output makes it possible for the variable speed units to operate stably even under system disturbances.[76] By variation of the operating point an optimization of the hydraulic and electric parameters is realized more easily and higher efficiencies can be achieved.

In pump mode at single speed operation frequency regulation is not possible due to the given system parameters namely hydraulic head and mass flow. In turbine mode, the unit cannot be operated at peak efficiency in part load. At variable speed at maximum hydraulic head where the machine comes close to the suction side cavitation limit the speed can be reduced to achieve pump inflow angles which better correspond to the geometry of the runner blades. Vice versa at minimum hydraulic head the speed can be increased to avoid pressure side cavitation and to extend the operating range to larger flow. Because of that we can differ between advantages on the turbine and/or pump side and advantages for motor/generator for the entire unit.

[75] Cf. Reviewing the Latest Technical Developments of Hydro Technology for Improved Performance Variable Speed

[76] Cf. Andritz Hydro-VariableSpeedTechnology-09/2011

There are four major advantages by using a variable speed unit:

1. Improved operation behaviour within a larger range of power
2. Increased efficiency at turbine/pumping mode
3. Increased generation due to enlarged operating field at turbine mode avoiding cavitation
4. Adjustable power in pumping mode at high efficiency

As mentioned above one advantage of the operation at best efficiency point is the improved cavitation behaviour. Less submergence is necessary which leads to reduced costs of the civil works which is a major part of the total costs of a new power plant.

Additionally variable speed units contribute to the grid stability better than fixed speed units. To support grid stabilization various capabilities can contribute to that:

- A fast dynamic response to support the grid requires instantaneous power generation adjustment capabilities. With primary frequency control settings sudden changes of power generation of e.g. other renewable energy sources as wind or solar power can be compensated.
- Load following or secondary frequency control leads to sustainable grid stabilisation in taking over the additional load which was compensated by the primary control units in order to unload them and making them available for other primary support tasks.
- At an adjustable speed machine the response rate is faster than of a conventional unit. At an asynchronous machine, not only by changing the turbine flow but under speed governor control due to varying the frequency of the rotor currents. This leads to a very fast control and electric transient response. Compared to a synchronous machine, where a full scale converter is directly connected to the grid decoupling the stator, and regulating the stator current.
- Adjustable speed motor/generators can use the rotating inertia of the machine and modulate instantaneous (short time) power fluctuations. This leads to an excellent behavior in case of grid faults.

Furthermore, the following advantages can be addressed:

- Longer service time of turbines because of the reduced noise, vibration and cavitation problems leading to improved availability
- New flexibility on the selection of site location and hydro unit size
- Relaxation of parameter requirements on machine design
- Less environmental impacts.

A summary of the general advantages of a variable speed unit can be seen in Table 5-2:

General advantages: variable speed vs. fixed speed	
Variable speed	**Fixed speed**
Extended range of operation (ratio max./min. head for variable speed approx. 1.25 to 1.45)	Extended range of operation (ratio max./min. head for fix speed approx. 1.25)
Improve operation behaviour: • Reduced pressure pulsation, • Reduced vibration	No additional losses of converter
Increased life time of the hydraulic machine	Lower investment costs
Better grid stability support (quick response to electric power demand)	
Increased annual generation	
Relaxation of parameter requirements on machine design	
Less environmental impacts	

Table 5-2: General advantages: variable speed vs. fixed speed[76]

In a conventional, fixed speed pump-turbine, the magnetic field of the stator and the magnetic field of the rotor always rotate with the same speed and the two are coupled. In a variable speed machine, those magnetic fields need to be decoupled. Either the stator field is decoupled from the grid using a frequency converter between the grid and the stator winding, or the rotor field is decoupled from the rotor body by means of a frequency converter directly connected to the multi-phase rotor windings.

Variable speed operation permits a fine tuning of the operating regime to meet the power adjustment needs of the grid. In this way the energetic balance of the power plant is improved. By improving the network balancing and the storage of excess power in hydraulic energy, the number of machine starts and stops is reduced.[77]

[77] Cf. G. Ciocan @all-Variable speed pump-turbines technology

5.2. Variable speed - turbine mode[78]

Focusing on the advantages of variable speed operation we can identify two main advantages at turbine mode:

- Increased generation due to operating at improved efficiency
- Increased generation due to enlarged operating field.

A separate explanation is shown below:

Increased generation due to operating at improved efficiency

For fixed speed operations the runner diameter and the speed do not operate at the highest possible hydraulic efficiency point within the turbine operating range. While the runner diameter is given and cannot be changed, the speed can be adjusted. The reduced speed shifts the whole turbine efficiency characteristics inside the operating range. In the entire operating range efficiencies are increased (see Figure 5-2 and Figure 5-3). Especially at medium and lower hydraulic heads and at part load this becomes much more important.

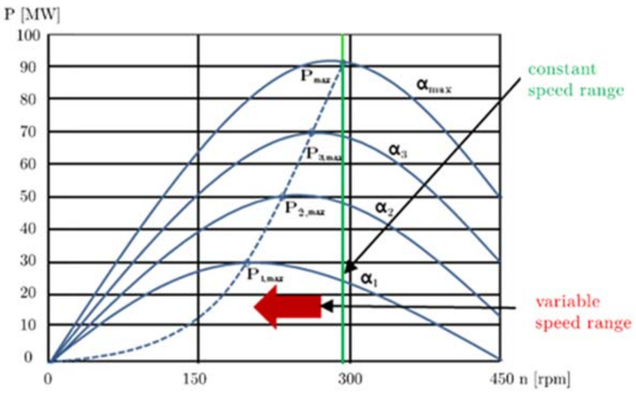


Figure 5-2 Output - speed curve of a Francis turbine (dotted line indicates best efficiency points)[79]

[78] Cf. Andritz Hydro-VariableSpeedTechnology-09/2011

[79] https://de.scribd.com/document/332995921/Hill-chart-of-Francis-turbine

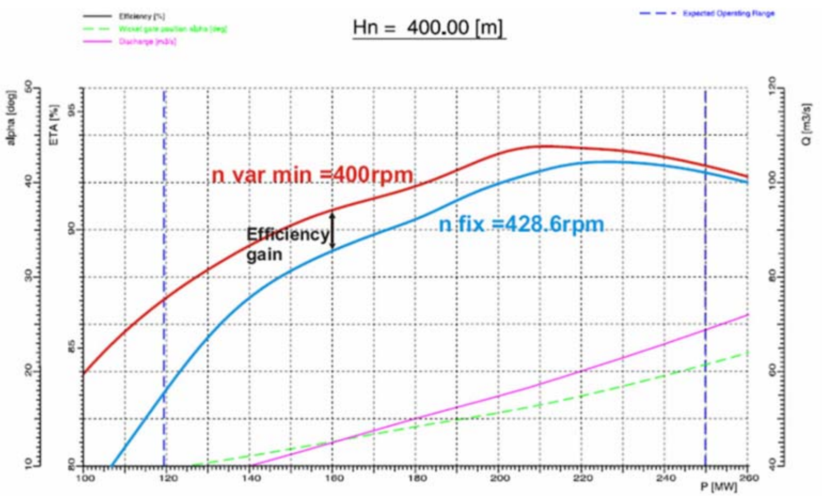
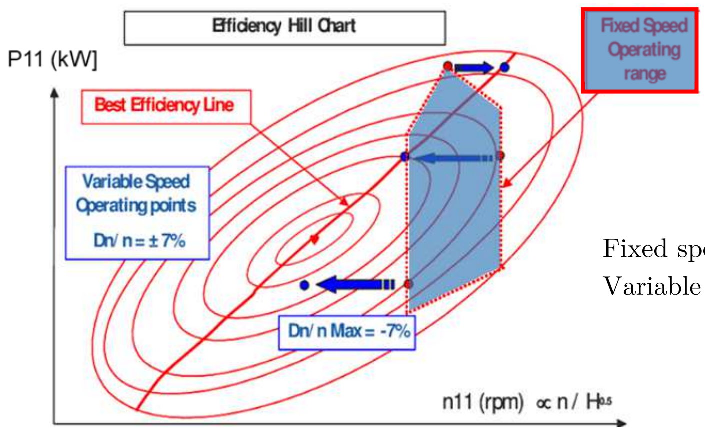


Figure 5-3 Turbine efficiency comparison fixed versus variable speed[80]

Figure 5-4 shows an efficiency hill cart in an optimised way (close range). It demonstrates the shift of the efficiency between fixed speed (red) and variable speed operating points (blue). While fixed operational speed the operation points are not at its best efficiency line, at variable speed the operations points are shifting towards the best efficiency line and better efficiencies can be achieved. If a modification of speed is possible, the efficiency can be optimized for given operating conditions. Moreover, the speed adjustment would avoid other problems that arise when the head deviations are excessive, namely draft tube pressure oscillations and cavitation.[81]



Fixed speed operating points red
Variable speed operating points blue

Figure 5-4: Optimised efficiency hill chart (close range)[82]

The speed factor n_{11} of a turbine is the speed of a turbine with 1 meter diameter at 1 meter head. The specific speed characterizes the turbine's shape in a way that is not related to its size. This allows a new turbine design to be scaled from an existing design of known performance. It is also the main criteria for matching a specific

[80] Andritz Hydro-VariableSpeedTechnology-09/2011

[81] J. Fraile-Ardanuy@all Variable-Speed Hydro Generation: Operational Aspects and Control- IEEE Transactions on Energy Conversion 07/2006

[82] G. Ciocan @all-Variable Speed pump-turbine technology UPB Scientific Bulletin-01/2012

hydro site with the correct turbine type. High specific-speed units are according to n_{11}- definition, units with low speed (and vice versa).

Fixed speed unit generation can only be optimized for one particular operating point. At part load or even flows above nominal flow at lower hydraulic head, fixed speed units do not operate in the vicinity of the optimum as shown in Figure 5-5. The efficiency hill chart shows the real best efficiency line and the operating points at constant or variable speed.

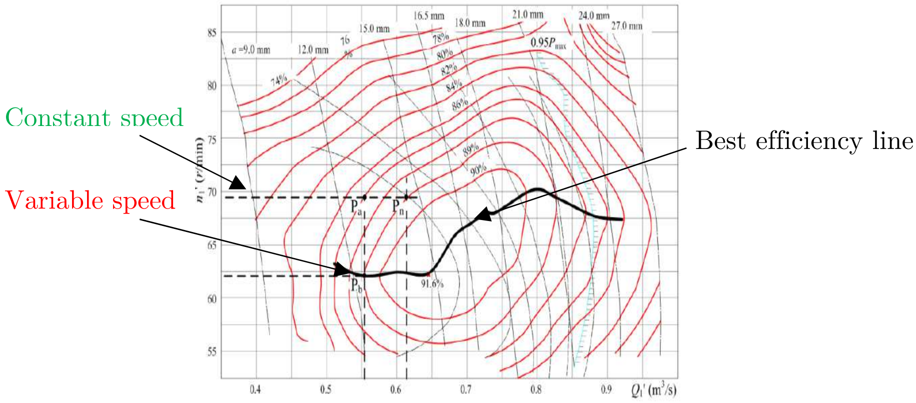


Figure 5-5: Real efficiency hill chart of hydraulic elements[83]

Based on the given power plant parameters such as hydraulic head or flow, variable speed turbines can be operated at the most efficient operating points. The efficiency of the turbine η_t is calculated from the ratio of the blade torque T, the angular velocity ω divided by the density of the water ρ, acceleration due to gravity g, head of water H and volumetric flow rate Q:

$$\eta_t = \frac{T_t \omega_t}{\rho g H Q_t} \tag{5.1}$$

Especially in part load operation, the efficiency can be enhanced by adjusting the speed to its optimum for the turbine corresponding to each available hydraulic head.

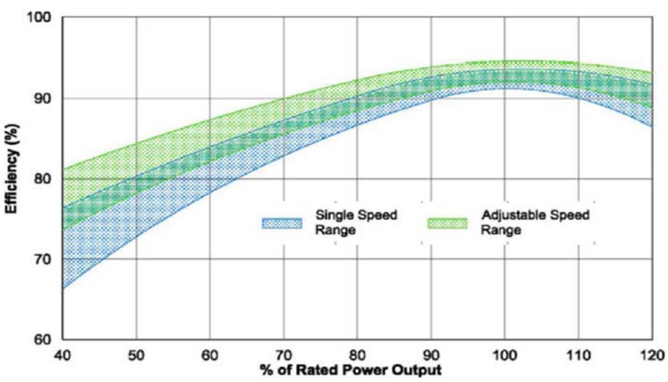


Figure 5-6: Efficiency comparison over power output[84]

[83] CIGRE AORC- Technical meeting 2014 – paper B4-1053

[84] M. Valavi; A. Nysveen:-Variable-Speed Operation of Hydropower Plants: Past, Present and Future

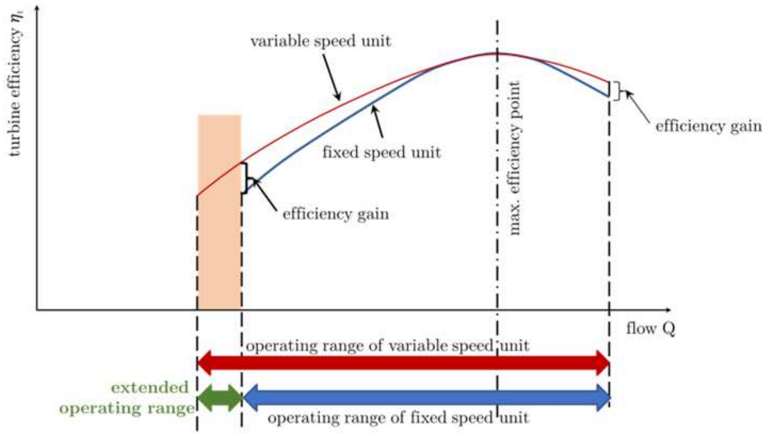


Figure 5-7 Efficiency gain over flow Q – comparison fixed versus variable speed[84]

The efficiency improvement because of variable speed operations leads to a higher power output and higher annual generation. Figure 5-6 and Figure 5-7 show the percentage gain of the power output respectively flow.

Increased generation due to enlarged operating field

The operating area of fixed speed units is limited by cavitation at the high flow side and for axial machines in the part load area additionally due to admissible vibration levels caused by draft tube oscillations.
In case of wider variation of operating head variable speed units can be operated in a much wider area of flow and hydraulic head without reaching the relevant operational limits thus resulting in a significant increase of power generation (Figure 5-8/Figure 5-4).

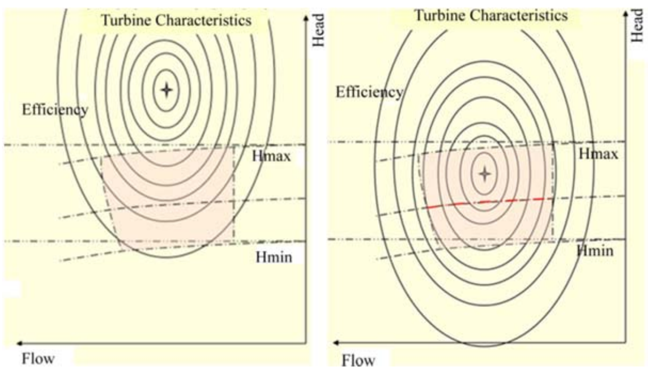


Figure 5-8: Turbine characteristics for fixed speed (left) and variable speed (right) operation[85]

[85] Andritz Hydro-Pumped Storage-02/2015

This enlarged operational field differs between the different types of hydro power plants. The following Table 5-3 shows the gains of variable speed operations in turbine mode.

Gains of variable speed operation at turbine mode	
Power plants	**Gains of variable speed operations**
Run-of-the-river small hydro plant	Significant gains in generated energy
Run-of-the-river hydro plants	Higher range of allowable flows in the turbine → continuity of operation → higher annual generation
Storage power plants/ Pumped storage power plant	Increased range of head variations → reduced need for flooded areas (reservoir size) running the turbine at better efficiencies →less water consumption / better energy conversion variable speed →less hydraulic problems (cavitation or draft tube oscillations) → reduced maintenance costs

Table 5-3 Gains of variable speed operation in turbine mode[85]

One example of a pumped storage power plant is one of the biggest PSPP with variable speed operation in Europe called Goldisthal (7.1).
It is equipped with four units, two single speed units and two with variable speed, each unit rated at 300 MVA. [86]

The ability to operate at the turbine's lower MW-range results in water savings, which can be used for later generation. Furthermore, variable speed units can be operated in a much wider range of flow and operating head without reaching the relevant operation limits thus gain in a significant increase of power generation. Variable speed technologies are not only for large units. Significant gains also for smaller ones are reported. For example, a really small sized variable frequency plant has reported about nearly doubled annually generated energy.[87]

[86] A. Beyer@all-06/ 2007

[87] G. Ciocan @all-Variable Speed pump-turbine technology UPB Scientific Bulletin-01/2012,

5.3. Variable speed - pumping mode

As addressed in 0 the advantages of variable speed in pumping mode are defined as follows:

- Improved efficiency in pumping mode
- Adjustable power in pumping mode

A separate explanation is shown below:

Improved efficiency in pumping mode

At fixed speed at larger hydraulic heads cavitation starts at the suction side of the runner blade inlet in pump mode. When changing towards lower heads, vapour pressure occurs at the pressure side of the blade in pump mode. An additional limitation occurs at the operation at large heads in pump mode due to instable flow phenomena in the hydraulic machine. Recirculation zones occur when the flow in pump mode minimizes and the pump pressure goes towards its maximum. Flow and power swings are the consequence which neither allows stable operation nor synchronisation. Variable speed operation can shift these cavitation limits and consequently enhancing the efficiency of the pump η_p, which is given by the ratio of the density of the water ρ, acceleration due to gravity g, head of water H and volumetric flow rate Q divided by the blade torque T and angular velocity ω:

$$\eta_p = \frac{\rho g H Q_p}{T_p \omega_p} \tag{5.2}$$

At maximum head where the machine comes close to suction side cavitation, the speed can be reduced to have pump inflow angles which better correspond to the geometrical runner blade angle. Vice versa at minimum head, the speed can be increased to avoid pressure side cavitation and to extend the operating range to larger flow (Figure 5-9). The above described cavitation effect occurs at extreme maximum and minimum head. At medium heads in the middle of the operating range the flow angle in pump mode corresponds much better to the geometrical blade angle. Therefore, cavitation behaviour in this range is much better. However, this advantage cannot be used in fixed speed operation.[88]

[88] Cf. J. Krenn @all-Small and Mid-Size Pump-Turbines with Variable Speed- 02/2013

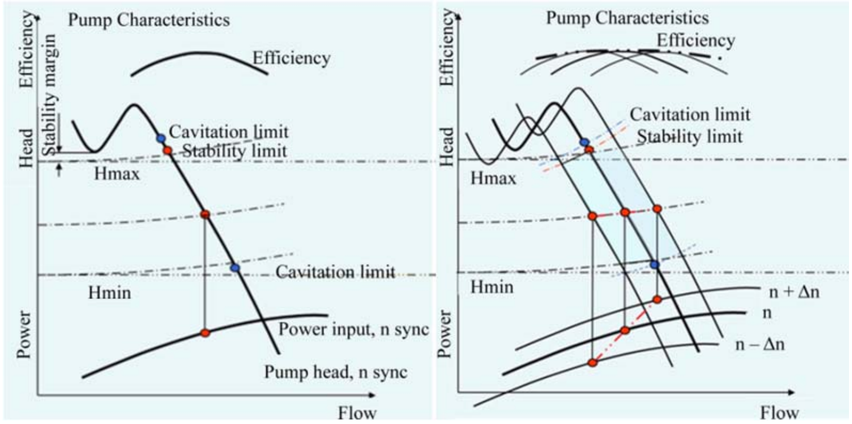


Figure 5-9 Pumping characteristics for fixed speed (left) and variable speed operation (right)[89]

Adjustable power in pumping mode

The input power during pumping mode cannot be changed at conventional pump-turbines with fixed speed operation and fine adjustments to compensate fluctuations in power are difficult. At fixed speed operation the pump input power is determined by the system characteristic and the reservoir level.

At pumped storage units in case of fixed speed units the pump operation point is only defined by the pump curve and the system characteristic. Therefore, control of the flow can only be achieved by means of a throttling valve (Figure 5-10).

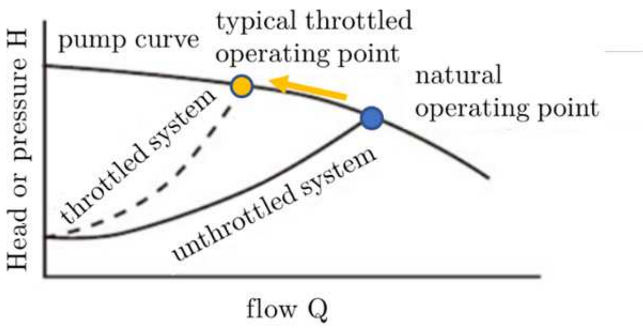


Figure 5-10 Throttled pump curve[90]

In case of variable speed the absorbed motor power P is proportional to ~n^3 and can be controlled in a wide range with rather small speed changes thus enabling to adjust power consumption in order to support grid stability in absorption of momentarily existing over-capacity. The power is defined as product of water head H, volumetric flow rate Q, acceleration due to gravity g and factor k:

$$P = H \cdot Q \cdot g \cdot k \tag{5.3}$$

[89] Cf. Andritz Hydro-Pumped Storage-02/2015

[90] Cf. http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

Out of this it can be derived that the area of the rectangles $H_i \cdot Q_i$ for each operating point is proportional to the absorbed pump power. As seen in Figure 5-10, it can be notified that, throttling is a very uneconomic way of flow regulation.

Instead reducing the centrifugal pump speed causes the pump curve to shift downwards as it can be seen in Figure 5-11. The shift leads to significant less power consumption at reduced flows compared to throttling.

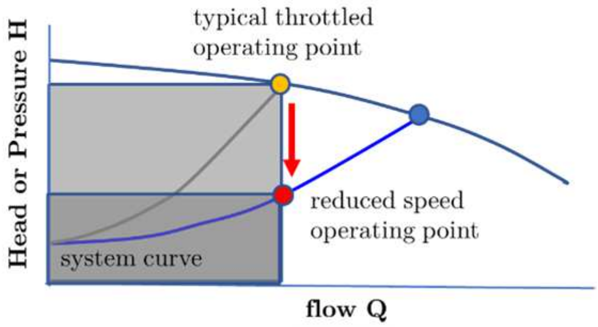


Figure 5-11: Pump curve reduced speed[91]

Depending on its power, size or speed, a pump can operate at any point up or down the system curve. Figure 5-11 shows how a basic performance curve of a variable speed pump will intersect the system curve at different speeds. The faster or the higher the pump speed, the more flow and hydraulic head the pump will generate. Conversely, the lower the pump speed, the lower the flow and hydraulic head the pump is generating, meaning you're working down the system curve.

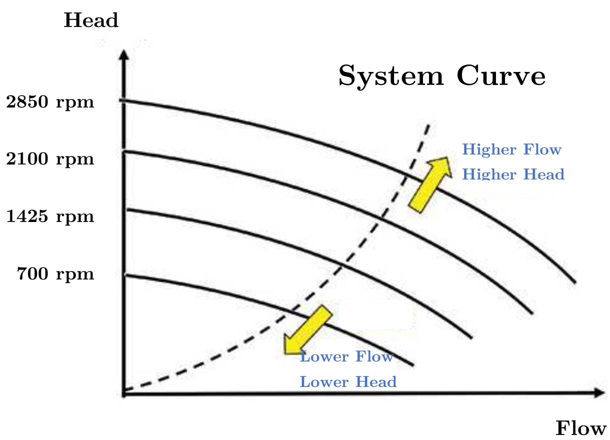


Figure 5-12 System curves of a variable speed pump[92]

A variable speed pump-turbine varies the flow and because of this its power is adjusted accordingly while the pump net head stays more or less constant. This leads

[91] Cf. http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

[92] Cf. Andritz Hydro-Variable speed operation of hydraulic turbines-10/2016

to water resource savings because less flow is required for the same pump input power and to the stability of the electric power supply (Figure 5-13).[93]

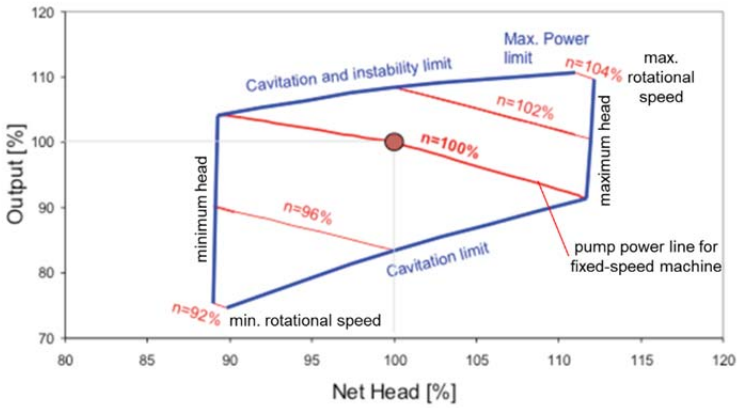


Figure 5-13 Effect of variable speed as % of rated speed on pump power absorbed[94]

At variable speed the power absorbed can be varied subsequently at fixed head, which permits a grid frequency regulation in pumping mode. Instead at fixed speed units can only regulate their power in generation mode and operate at fixed power in pumping mode. The variation of the speed can lead up to approx. 30 % of the absorbed power (Figure 5-14).[95]

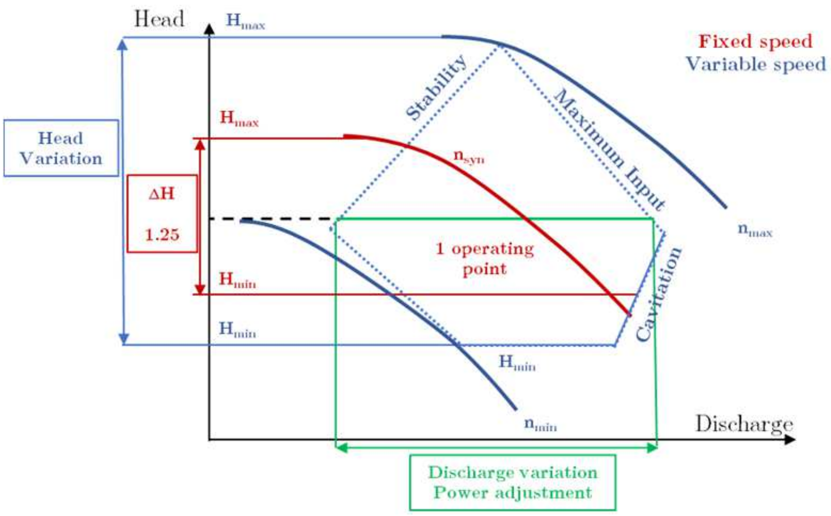


Figure 5-14 Operating domain for fix speed (red) and variable speed (blue): grid frequency regulation[92]

[93] Cf. http://www.vfds.org/vfd-for-centrifugal-pumps-662716.html

[94] Cf. Advantages of Variable Speed Pump Turbines for adjusting Power Supply -Mitsubishi Heavy Industries Technical Review Vol. 48 -09/2011

[95] Cf. G. Ciocan @all-Variable Speed pump-turbine technology UPB Scientific Bulletin-01/2012,

5.4. Variable speed motor/generator

When we want to introduce a variable speed solution, we have to overcome two aspects:

- In case of a fixed speed synchronous machine stator field and rotor field are locked. Rotational speed is depending on grid frequency and number of poles. As pole quantity is to be seen as a constant the stator frequency has to be altered with a full scale converter in order to change speed.

- In case of an induction machine we have to differentiate whether we have a squirrel cage or a wound-rotor machine.
  In case of a squirrel cage machine the only parameter to change the speed at a given load is to alter the stator frequency. However, in case of a wound rotor machine we have the possibility to change the speed by feeding the rotor with an alternating current provided by a converter.

- The consequence of aforesaid is that the rotational speed of the magnetic field must be decoupled from its classical generating origin: either on stator side decoupling the stator field from the grid frequency, or on rotor side decoupling the rotor field from the rotor body.

The first solution, synchronous unit and a squirrel cage unit require a frequency converter between the grid and the stator winding; the second solution applicable for the wound rotor machine can have a frequency converter between the grid and the rotor as it requires a magnetic field rotating around the rotor, realized by a three-phase rotor winding fed via a frequency converter connected to the rotor.

Currently three technologies are competing at the marketplace in terms of variable speed motor-generators:

- Doubly fed induction machine with an inverter on the rotor side
- Synchronous machine with full scale inverter on the stator side
- Induction machine with a full scale inverter

Principles of speed variation

- Motor-generator with at most two winding-systems with variable number of pole pairs
  - Only two dedicated speeds possible - two fixed speeds
  - Complicated windings and winding connection system necessary
  - No longer state of art (built in 1960..1980s)
  - Speed varies with pole pairs

- Rotor connected converter (doubly fed asynchronous machine)
  - Limited speed variation (e.g. ±15% of synchronous speed)
  - Converter size depends on speed range, usually much smaller than rated machine power
  - 3-AC converter output connected to rotor via slip rings
  - High efficiency

- Stator connected converter (full size frequency converter)
  - Continuous speed variation
  - Converter size = approx. 100% of the machine output
  - Simple generating unit (synchronous or asynchronous)
  - Generation/Consumption and in-feed into grid widely decoupled
  - Speed of machines varies by frequency

Below a schematic comparison of the two new technologies (Figure 5-16 and Figure 5-17) compared to fixed speed PSPP (Figure 5-15) are shown:

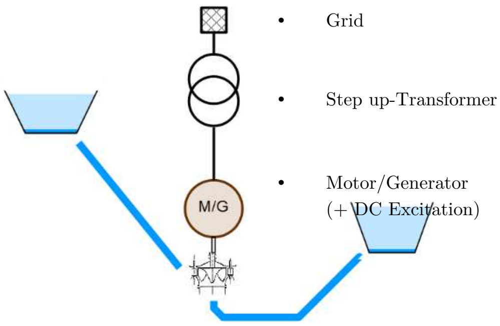


Figure 5-15 Fixed speed setup PSPP[96]

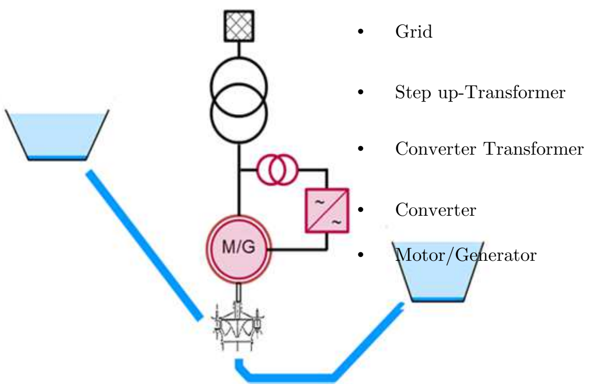


Figure 5-16 Variable speed setup with doubly fed induction converter machine (DFIM)[96]

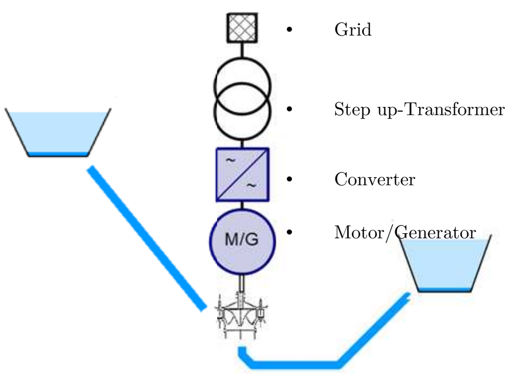


Figure 5-17 Variable speed setup with a full scale converter (FCSM)[96]

[96] Andritz Hydro-Benefits of variable speed pumped storage plants-11/2014

5.4.1. Doubly fed induction machine (DFIM)[97]

As we have discussed the main aspects of the slip ring machine in chapter 4.2.2. We will now have a more detailed look at the doubly fed asynchronous machine which in order to realised variable speed is supplied with independently excited multiphase windings on both rotor and stator. The equation circuit can be seen in Figure 4-9.

The equations of the DFIM with rotor standstill voltage u_{20}, the slip s and the efficiency $\cos\varphi_1$ are as following:

$$U_2 = s \cdot U_{20} \quad (5.4)$$

$$cos\varphi_{1m} = cos\varphi_1 \text{ of the machine} \quad (5.5)$$

The active power and reactive power of the machine (m) and the rotor (R) are:

$$P_m = m \cdot I_2 \cdot U_2 \cdot \cos(\varphi_{1m}) = \frac{P_D}{\eta} \quad (5.6)$$

$$Q_m = m \cdot I_2 \cdot U_2 \cdot \sin(\varphi_{1m}) \quad (5.7)$$

$$P_R = s \cdot m \cdot I_2 \cdot U_2 \cdot \cos(\varphi_{1m}) = s \cdot \frac{P_D}{\eta} \quad (5.8)$$

$$Q_R = m \cdot I_2 \cdot U_{20} \sqrt{s_{max}^2 - \frac{3}{4}s^2} \quad (5.9)$$

$$P_{total} = P_m - P_R = m \cdot I_2 \cdot U_2 \cdot \cos(\varphi_{1m}) \cdot (1 - s) \quad (5.10)$$

$$Q_{tot} = Q_m + Q_R \quad (5.11)$$

The doubly fed induction machine system can be considered as the current state-of-the-art of variable speed PSPPs. It has a high efficiency and lower additional costs than a full-size frequency converter, since the frequency converter only needs to be rated to provide power as a fraction of the rated power, depending on the desired speed-range. However, such systems do not allow starting the pump directly in water (requiring additional time to de-water the pump). Furthermore, achieving compliance with the latest grid requirements for low voltage ride through (LVRT) is often challenging and hence costly.

In most of the large PSPP, the DFIM technology is implemented. DFIM uses the exchange between the wound rotor and frequency converter to provide the speed variation. As a consequence, the stator needs to be oversized, due to the additional power transiting into the sub-synchronous generator and super-synchronous inventor.

In both cases, the main constraint on the DFIM design is to fit stator and rotor within the motor/generator pit. The pit dimensions are a limiting factor to the DFIM

[97] Cf. Andritz Hydro- The generator for variable speed-01/2018

maximum output. With the same rated power a DFIM wound rotor is about 30% heavier than a salient pole synchronous rotor, which impacts the shaft line behaviour.

This system allows a variable speed operation over a large, but restricted, range. The converter compensates the difference between the mechanical and electrical frequency by injecting rotor currents with a variable frequency. Both during normal operation and faults the behaviour of the machine is thus governed by the power converter and its controllers. The power converter consists of two converters, the rotor-side converter and the grid-side converter, which are controlled independently of each other. In both cases – sub-synchronous and super-synchronous generation - the stator feeds energy into the grid in generation mode whereas at sub-synchronous and super synchronous motor mode the machine consumes energy.

In case of a weak grid, where the voltage may fluctuate, the DFIM may be ordered to produce or absorb an amount of reactive power to or from the grid, with the purpose of voltage control. The converter used in DFIM is preferably is a bidirectional power converter consisting of two conventional pulse-width modulated converters. The capacitor between the inverter and rectifier makes it possible to decouple the control of the two inverters without affecting the other side of the converter. The power flow at the grid-side converter is controlled to keep the DC link voltage constant, and the control of the machine-side converter is set to suit the magnetization demand and the desired rotor speed.

The task of the frequency converter is to transfer the slip energy from the rotor side to/from the grid and to provide excitation for the motor/generator. The energy flow for different load cases is illustrated in Figure 5-18. Due to the speed variation the distribution of the energy flows between the stator and the frequency converter changes according to the network requirements.

Turbine operation:

- The main energy flow is from the turbine (mechanical energy) over the air-gap of the motor/generator to the network
- If the speed is higher than the synchronous speed a part of the energy is transmitted to the network via the sliprings and the frequency converter
- If the speed is lower than the synchronous speed a part of the energy needs to be injected via the frequency converter onto machine via sliprings

Pumping operation

- The main energy flow is from the network over the air-gap of the motor/generator to the turbine
- If the speed is higher than the synchronous speed a part of the energy needs to be injected via the frequency converter onto machine via sliprings
- If the speed is lower than the synchronous speed a part of the energy is flowing back over the sliprings and the frequency converter to the grid

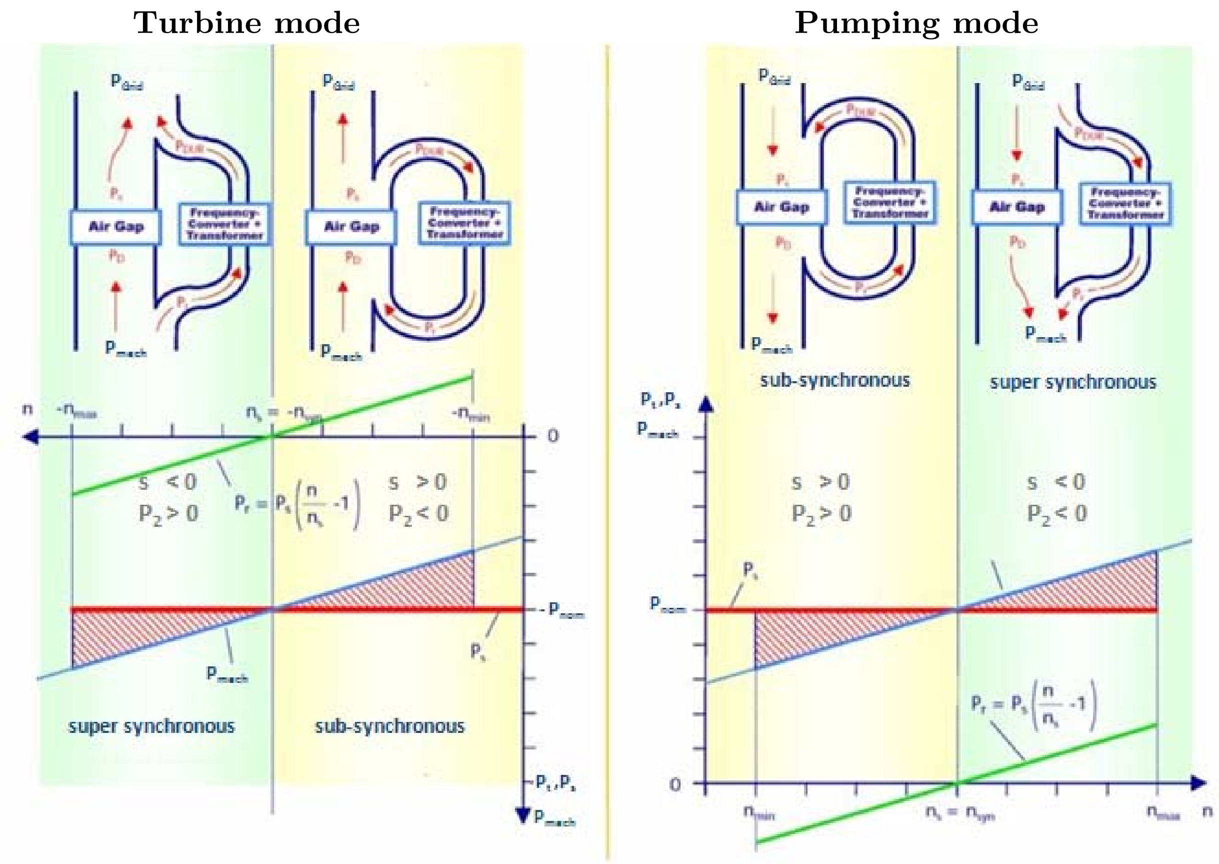


Figure 5-18 Comparison super- and sub-synchronous power characteristics at turbine/pumping mode[98]

98 Cf. Andritz Hydro -Variable Speed Hydropower Plants, 11/2011

5.4.1.1. Design of a DFIM[90]

The structural design of the asynchronous machine with a wound rotor compared to a salient pole synchronous machine is different only on the rotor side. All the static components such as stator core, stator frame, stator winding, bearings, bearing bracket etc. are for both of the same design concept. It has to be considered, that asynchronous machines have a rather small air gap the more pole pairs used, therefore particular care has to be taken to ensuring roundness and concentricity of stator and rotor.

The rotor is equipped with a conventional three-phase winding which is fed by at least three sliprings by a three-phase current system at the actual rotor frequency. The design has to fulfill the following requirements:

- The rotor rim with the three-phase winding must be designed to meet minimum iron losses considering the frequency, and must be in accordance with the specified limits such as temperature rise and mechanical stress.
- The rim must be equipped with a cooling system, by radial air ducts for the cooling air or with water cooling in bars next to the rotor windings.
- The overhang of the rotor winding must be supported properly for all mechanical and thermal conditions.

For asynchronous machines, up to a bore diameter of about three meter the rotor winding overhang is normally supported by a prestressed bandage of stainless-steel wire. The fitting of this bandage is very difficult due to the required thermo-mechanical process and in case of a break-down of Roebel bars in the rotor winding the whole bandage must be removed. Furthermore, the cooling of the overhang is strongly reduced. For larger machines, an end winding support concept based on retaining bolts is applied.

To minimize the iron losses, the rotor rim consists of high strength steel sheets with a thickness of less than one millimeter which are stacked to form the rotor rim. The laminated ring has radial air ducts and is fixed onto the hub by means of special wedges. The wedges are arranged around the circumference in such a way that concentric radial movements of the rotor rim, resulting from the centrifugal force, are possible. On the outer periphery of the rim there are slots into which a three-phase winding is placed, which in turn is secured against forces acting in the radial direction by non-magnetic slot wedges.

The supporting ring is assembled by stacking two to six millimeter thick sheet - steel segments to form single rings which are pressed together using prestressed shear-pressing bolts, resulting in a homogeneous ring. The single rings are separated from each other by the use of specially designed spacers. The cooling air flows between the individual rings to the winding overhang. Around the outer circumference, threaded templates are slid into axial T-shaped slots.

Radial bolts are passed through the spaces between the upper and lower winding bars and screwed into the threaded templates. Insulating pads under the bolt heads guarantee an even pressure distribution in the bars in the region of the winding overhang.

The machine/rotor design is the most impacted by this new technology. Three main parts are completely different compared with classical machines: sliprings, winding overhang retaining system and rotor rim.[99]

Slipring:

To feed the rotor with the three-phase current system, at least one slipring per phase and usually one slipring for the star point are needed. In normal operation, the frequency of the currents is low. At synchronous speed, the currents become constant. During rotor start at rotor speed at n=0 the rotor windings sees the full frequency whereas with increasing speed the frequency reduces to 0.
The brush system and the sliprings need to be designed for these requirements. For a regular wear of the carbon brushes air temperature and humidity need to be controlled. Special attention has to be paid to an even distribution of the currents on the different carbon brushes.

Winding overhang retaining system:

The rotor winding overhang has to be supported to avoid deformation and damage if the machine speed comes close to runaway speed during load rejection. Three basic concepts can be used:

- The first concept uses a steel retaining cap similar to the design used in turbo generators. The caps can be shrunken and are dismountable. The steel cap needs to withstand high mechanical forces and is made of forged nonmagnetic steel.

- For the second concept, the whole overhang is bandaged either by a steel or synthetic wire or a synthetic foil. The application of the wire or the foil needs special tools. Dismantling of the system without destruction of the bandage is generally not possible. Special attention needs to be paid to the cooling of the winding overhang for the first two solutions, because the cooling airflow cannot pass through the winding overhang in radial direction.

[99] Cf. A. Schwery, T. Kunz- Variable Speed, Technology and Current Projects in Europe-07/2009

- The third concept consists in a set of retaining bolts that fix the winding overhang to an auxiliary rim mounted on the rotor rim. Cooling air can directly pass through the winding overhang in radial direction. Furthermore it is possible to dismantle individual bars if required. A strict quality process defining individual checking of each bolt is required due to the huge mechanical solicitation of these bolts.

Rotor rim:
Similar to the winding overhang retaining system, the rotor rim is also exposed to mechanical rotating. Since the rotor rim consists of a highly inhomogeneous stack of varnished steel laminations, it is advisable to cross check the calculation by practical tests. In contrast to the rotor rim of a salient pole machine, the rim of an induction machine is carrying an alternating magnetic field. To reduce the iron losses created by eddy currents and hysteresis materials with low loss coefficients can be used. Generally materials with high field strengths have relatively high magnetic loss coefficients. The right compromise is to be found between the mechanical and magnetic proprieties of the material.

5.4.1.2. Advantages/disadvantages of a DFIM

To summarize all advantages and disadvantages of a doubly fed induction machine, a detailed list it shown below:

Advantages

- Instead of being dissipated, most of the rotor energy can be fed back into the grid via the power electronic converter during sub-synchronous operation. At super synchronous operation additional energy has to be fed into the rotor

- Ability to control reactive power both for leading and lagging

- DFIM supports variable speed range operation; typically ±15% around the synchronous speed

- The rating of the power electronic converter is only 15%...20% of the machine power, which makes this concept attractive from an economic point of view

Disadvantages

- DFIM has brushes which need regular inspection and replacement. They are a potential cause of machine failure and electrical losses thus leading to lower reliability and availability
- Under grid fault conditions, large stator currents result in large rotor currents, so that power converter needs to be protected from destroy
- Higher harmonics due to the converter, within the rotor windings, in particular counting additional power losses as well as torque oscillations

5.4.1.3. Reasons to use a DFIM for hydro power generation[100]

Although there are some noticeable drawbacks the doubly fed asynchronous machine is nowadays very common for hydro power generation, therefore the reason for using it especially with larger units are visualized below:

- The speed can be altered within a sufficiently large range of normally ± 15 % of the synchronous speed. This speed variation corresponds to a maximum power variation of ± 30 %. This feature allows the utility to pump with variable load or to generate with partial load but optimum efficiency.
- The converter has to be sized according to the slip power. The greater the required speed adjustment range is in relation to the synchronous speed, the greater the slip power is and therefore the required converter size will increase. The cycloconverter or pulse width modulation PWM converter has to be sized for the power related to the speed range and the required reactive power. The current limit in the rotor circuit is given by the thermal stresses on the rotor.
- Due to the fact that the speed may be altered in a certain speed range, the machine may also be used for instantaneous power injection to the grid. This feature will allow to reduce the spinning reserve in an existing grid.

[100] Cf. D. Schafer, J .Simond -Adjustable speed Asynchronous Machine in Hydro Power Plants and its Advantages for the Electric Grid Stability-01/1998

5.4.2. Synchronous machine with full scale inverter (FCSM)

A FCSM can be designed with a full scale power converter that has to handle the full power of the system.

At synchronous machines with variable speed operation mainly integer-slot windings are used. Although they produce larger harmonics, they have the advantage to generate fewer vibrations. However, the advantages of fractional slot windings as e.g. the improved voltage curve and the better distortion factor are not longer of large interest because of the impact of the inverter.

5.4.2.1. Advantages/disadvantages of a FCSM

To summarize all advantages and disadvantages of a synchronous machine with full scale inverter, a detailed list it shown below:

Advantages

- The full scale power converter can perform smooth grid connection over the entire speed range
- This concept has the opportunities of controlling the flux for a minimized loss in different power and speed ranges, because the excitation current can be controlled by means of the excitation system at the rotor side
- It does not require the use of permanent magnets, which would represent a large fraction of the machine costs

Disadvantages

- It has a higher cost and a higher power loss in the power electronics, since all the generated power has to pass through the power converter
- It is necessary to excite the rotor winding with a DC current, using sliprings and brushes, or brushless exciter, employing a rotating rectifier and consequently the field losses are inevitable
- In order to arrange space for excitation windings and pole shoes, it becomes a heavy weight and expensive solution
- Significant space requirements for the converters for larger units

However it is mentionable that the preceding progression of power electronics will increase the power electronics will the power range of the full scale converters persistently.

5.4.3. Permanent magnet synchronous generator with full scale inverter (PMSM)[100]

The use of permanent magnet excitation requires the use of a full scale converter in order to adjust the voltage and frequency of generation to the voltage and the frequency of transmission, respectively. However, the benefit is that power can be generated at any speed so as to fit the current conditions. The stator of PMSMs is wound, and the rotor is provided with a permanent magnet pole system. The synchronous nature of the PMSM may cause problems during start-up, synchronization and voltage regulation. Contrarily to the DC-excited SM, PMSM does not readily provide a constant voltage.

The permanent magnets are mostly made of Neodyn material, it is rare and the magnetic materials are sensitive to higher temperatures, meaning temperatures above approx. 200° C the magnets will lose its magnetic character. Therefore, the rotor temperature of a PMSM must be supervised and a proper cooling system is required. PMSMs at hydro power plants are normally used as start-up units of vertical shaft units and at smaller sizes up to about 10 MVA.

5.4.3.1. Advantages/disadvantages of a PMSM with full scale inverter[101]

The advantages/disadvantages of a PMSM with full scale inverter are listed below;

Advantages

- The full scale converter can perform smooth grid connection over the entire speed range
- Higher efficiency and energy yield
- No additional power supply for the DC-field excitation
- Improvement in the thermal characteristics of the permanent magnet machine due to the absence of the field losses
- Higher reliability due to the absence of mechanical components such as slip rings and brushes
- Lighter and therefore higher power to weight ratio

[101] Cf. Andritz Hydro-The generator for variable speed-01/2018

Disadvantages

- It has a higher cost and a higher power loss in the power electronics, since all the generated power has to pass through the power converter
- High cost of permanent magnet material
- Difficulties to handle in manufacture
- Demagnetization of permanent magnet at high temperature
- Significant space requirements for the converters for larger units
- Due to the permanent magnet, higher speeds request for controlling the converter to avoid over-voltage

5.4.3.2. Conversion of a small fixed speed hydroelectric units into a variable speed[102]

In this chapter you will find an extract from the technical report about the conversion of the 50 kVA unit of the Weisenberger Mill in Kentucky, USA, which was supported by the US department of energy (DOE).

The project was titled "Demonstration of variable speed permanent magnet generator at small low-head hydro site" and was executed between 2011 and 2012. Small low-head, run-of-river-type sites are facing frequent changes in hydraulic head causing the turbine to run off its peak efficiency. At small sites, small changes in head can already lead to dramatic losses in efficiency. Variable speed units can be operated in a much wider range of flow and operating head without reaching the relevant operation limits thus resulting in a significant increase of power generation. The example of the Weisenberger mill in Kentucky provides inside details about the improvements and challenges for an application at a small low-head hydro site. Before modernization the mill had a 50 kVA induction machine with a belt drive transmission system. Induction machines, which are the most commonly used machines in small and mini hydro applications, have their own set of problems. While they are inexpensive to purchase and easier to install, they are less efficient and have significant power factor limitations, especially at lower speeds. There are also limits on machine size. Low head sites that require slow speed turbines are a poor match with induction machines that run more efficiently at higher speeds.

During the modernization only machine and control were changed. A permanent magnet machine was chosen and connected via a converter to the grid. The variable

[102] Cf. Andritz Hydro-The generator for variable speed-01/2018

speed feature allows the turbine to operate at its optimum speed at any given power input level, instead of running at a less efficient speed dictated by the generator.

Additionally, the permanent magnet design provides efficiencies as good, or better, than that of synchronous machines. As the PMSM can easily be built to meet the turbine rated speed it and be directly coupled, it does not need gearboxes, belts or other speed increaser systems. On the electric side compared to a synchronous generator system the power converter eliminates the need for excitation, contactor, voltage regulator, auto synchronizer and speed matching control.

The PMSM system was able to produce almost twice as much power as the IM system, in the maximum net head range of 2,4 to 2,7 meter. At about 1,7 meter, the output from the IM system had dropped to zero, and below 1,7 meter, the induction machine was "motoring", or drawing more power than it was producing. In contrast, the PMSM system was able to produce positive power down to 0,6 meter of net head and below.

So the large increase in power output between the old and the new system was due to two major factors:

1. PMSM can adjust speeds according to varying net heads
2. the old IM system had been running at a too high speed

Using the flow duration curve for this site, the original IM system was expected to produce 92,516 kWh, while the PMSM system with a variable speed drive is projected to produce 181,412 kWh. Thus over an average year, the PMSM system should produce about 96.1% more energy than the IM system it replaced.

An additional benefit of the replacement of the IM system with the PMSM system is a significant improvement in power factor. The old IM system, with a 900 rpm induction machine operating at about 25% load, had a power factor at 45 % or even lower, depending on the machine loading. This resulted in substantial reactive power being supplied by the connecting utility. In contrast, the PMSM system operated near a unity power factor until the head dropped very low and the machine was very lightly loaded, which occurs rarely. With regard to economy the payback period of the investment it is reported that the equipment cost will be earned by the additionally generated energy after seven years.

5.5. Power Electronics - Converter Systems

For variable speed systems in pumped-storage power plants, the frequency converter is a very important element and a major cost driver. It enables variable speed operation, smooth starting, regenerative and dynamic braking as well as reactive power compensation and also makes active power filtering possible. Optimisations of costs have led to different concepts which offer best value for money in their respective segment of application.

In variable speed technology, static frequency converters are used to vary the speed of the electrical machine. For machines – less that 75…100 MVA – a synchronous machine is linked to the grid by a static frequency convertor. For larger units, this solution is not justified economically. For units larger than 75-100 MVA doubly fed induction machines with a static frequency converter feeding the rotor are the preferred solution.[103,104]

For variable speed applications, there are two different types of converters used:

- Line- and/or load-side commutated converters (LCC)
- Forced commutated converters (FCC)

5.5.1. Line-side commutated converters (LCC)[105]

At line commutated converter the commutation voltage, i.e. the voltage required to transfer current from one device to the other, is provided by the supply to which the converter is connected.

If the converter has thyristors in all positions it is called a fully-controlled converter. On the other hand diodes can be used in a few positions of the converter. They can perform only phase-controlled rectification, and we talk then about a half-controlled converter.

The half-controlled converter is easy to be build and has the advantages that the reactive power of the control can be significantly smaller compared to a fully-controlled converter. Nevertheless, no negative output voltages are possible.

Because of this fully-controlled converters are more convenient in pumped storage power plant applications.

[103] Cf. A. Schwery, T. Kunz- Variable Speed, Technology and Current Projects in Europe-07/2009

[104] G. Cocan@all-Variable speed pump-turbines technology-01/2012 -U.P.B. Sci. Bull

[105] Cf. Anders Carlsson- The back to back converter - control and design, 10/1998; Lund Institute of Technology

LCCs are rather simple and robust in design but have certain disadvantages as:

- high low-order harmonics in the line current causing distortion of the voltage curve on the load-commutated inverter side
- these harmonics cause additional losses in the machine
- the line-side power factor of such converters is always inductive and cannot be controlled
- high demand for reactive power when the output voltage is low

One example for a line-side converter is the cycloconverter, see in Figure 5-19. It is a type of power electronic converter which provides variable AC voltage of variable frequency without DC link. Cycloconverters, which were used in earlier times [Ohkawachi, Japan, 1993; Goldisthal, Germany, 2003] due to their advantages compared to LCCs, as:[106]

- Generation of low-frequency AC voltage
- Instantaneous real and reactive power control
- Low on state power losses

However due to the disadvantages, as:

- Inability to generate output voltage with a frequency greater than input frequency
- Requirement of additional static frequency converter during starting in pump mode
- High distorted rotor current in DFIM, thereby introducing the large size of filters compare to voltage source inverters
- Reactive power absorption from grid at rotor side

[106] Cf.J. Anto @all- A Review of Power Electronic Converters for Variable Speed Pumped Storage Plants- 03/2018- IEEE JOURNAL of emerging and selected topics in power electronics Vol. 6

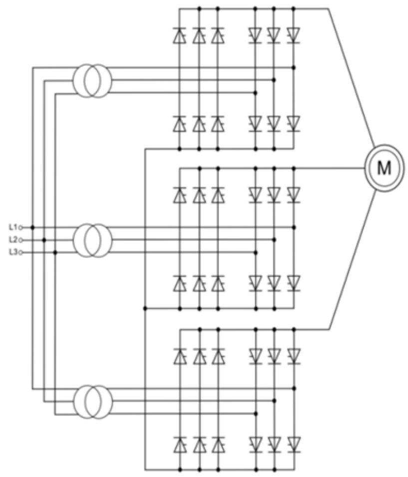


Figure 5-19 Cycloconverter[107]

Since the 1990s, cycloconverters have been used on the rotor side of DFIM. However, they are now being phased out gradually due to high ripples in rotor current and reactive power consumption from grid as well as rotor side. Presently, the two-level and three-level back-to-back voltage source inverter are preferred owing to its less total harmonic distortion and unity power factor on the grid-side of the rotor.[108]

When using LCC technology various methods have been developed at line-side in order to reduce/eliminate the influence on the power grid. Some of these methods are:

- Filters and multiple series resonant links
- Third harmonic injection
- Twelve-pulse operation
- Multi-level rectifiers
- Forced commutated rectifiers (e.g. PWM-rectifiers)

All this has a significant cost effect on the total converter system costs, therefore with the development of power transistors forced commutation became cost effective and enabled the widespread application of variable speed.

[107] https://circuitdigest.com/tutorial/cycloconverter-types-working-circuits-applications

[108] J. Anto @all-Reliability of Variable Speed Pumped-Storage Plant- 09/2008

5.5.2. Forced commutated converters (FCC)

As for small applications the harmonic distortion does not have a serious impact on the voltage quality, in the MW range of applications the distortion is already affecting the energy quality. At industrial and energy applications the following aspects have to be carefully evaluated before decision of investment.

- Meeting the limits of allowed harmonic voltage distortion in networks
- Line side power factor resp. reactive power control
- Redundancy

Today back-to-back converters (Figure 5-20 and Figure 5-21) are said to be the most efficient and cost effective solution for large variable speed applications.

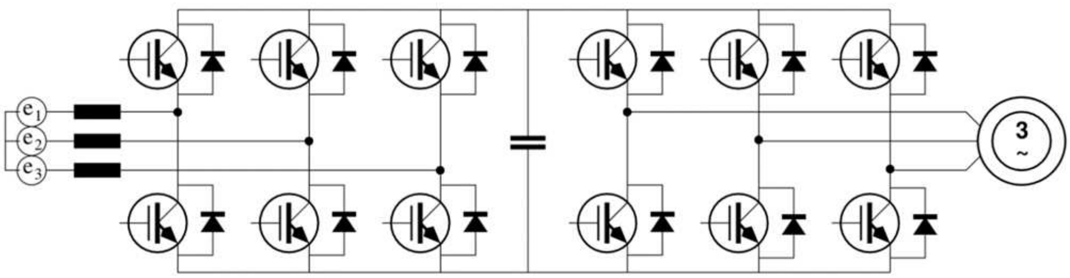


Figure 5-20 Two-level back to back converter[109]

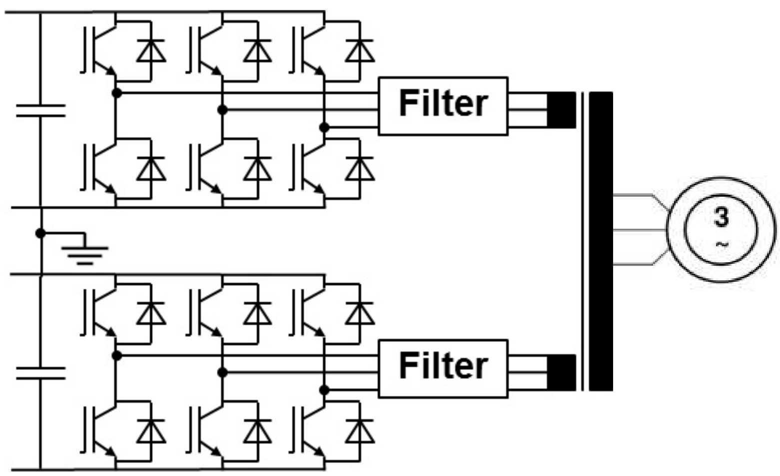


Figure 5-21 Three-level back to back converter[109]

[109] Anders Carlsson- The back to back converter - control and design, 10/1998; Lund Institute of Technology

It consists of a force commutated rectifier and a force commutated inverter connected with a common DC link, see Figure 5-20. The properties of this combination are:

- The line-side converter may be operated to give sinusoidal line currents, causing less harmonic distortion to the line voltage
- Possibility of fast control of the power flow, enabling the reduction of the size of the DC link capacitor, without affecting inverter performance, thus reducing costs
- Finally using the forced commutation enables the possibility of controlling the line-side power factor as well as the machine
- An advantage in certain applications is that braking energy can be fed back to the power grid thus a breaking resistor is not needed[110]

Redundancy and protection of the power converter connected to the rotor are considered the most important operational challenges in DFIM-fed variable speed PSPP.
Power converters used in doubly fed variable speed PSPP have to cope with a number of tasks as:

- Variable speed operation
- Smooth starting
- Regenerative and dynamic braking
- Reactive power compensation
- Acting as active power filters
- Achieving real and reactive power control in generation mode
- Providing speed and reactive power control in pumping mode

The largest full scale frequency converter as to the author's knowledge is the 100 MVA Grimsel 2 converter (7.2.). The converter is configured in two blocks, each with 50 MVA capacity, on the line- and motor-sides. The main limitations of Grimsel 2 are the capacity of the power electronics, which must be equal to the total capacity of the connected synchronous machine.[111]

Other technologies like back to back voltage source inverter systems took gradually over. Back-to-back voltage source inverters are the inverters which have widespread applications including the control of doubly fed based variable speed PSPP. Such converters have an ability to provide variable voltage and variable frequency supply during starting of the machine resulting the reduction of start-up transients and energy losses.

[110] Cf. Anders Carlsson- The back to back converter - control and design, 10/1998; Lund Institute of Technology

[111] E. Bortoni @all- The Benefits of Variable Speed Operation in Hydropower Plants Driven by Francis Turbines- 03/2019- Energies 2019

Figure 5-22 shows the typical single line diagram of a back to back converter consisting of parallel converter blocks feeding a very large DFIM. The crowbar is for emergency shut-down to protect the converter from being seriously damaged.

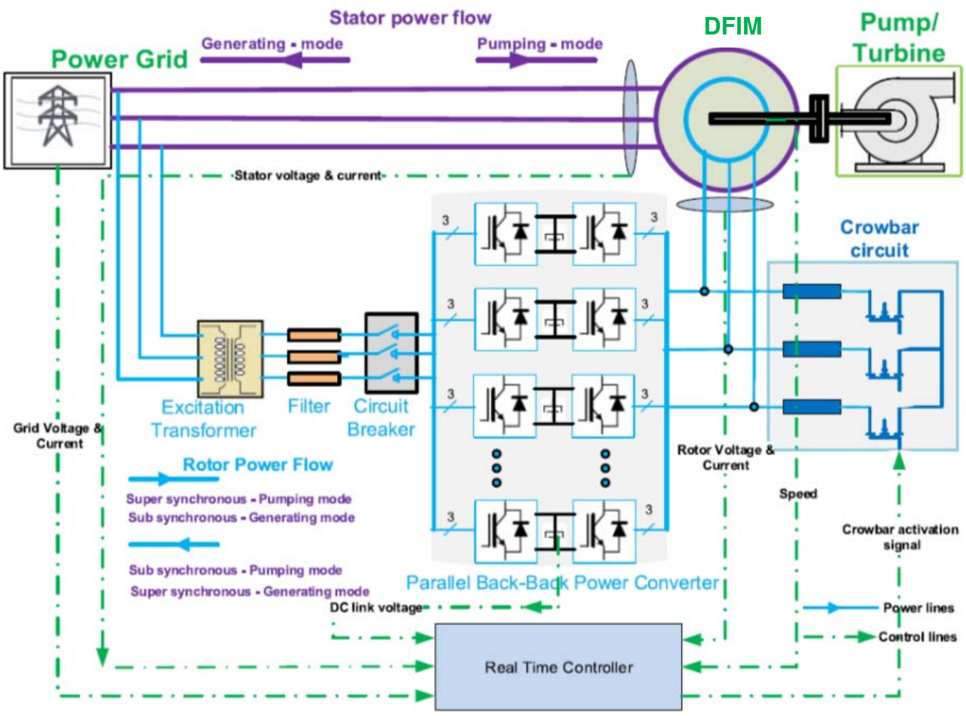


Figure 5-22 Parallel back to back converters feeding a DFIM pumped storage unit[112]

Parameter	Cycloconverter	DC link converter
Principle	converts AC at on frequency to AC at some other it a single stage power conversion	uses two power stages AC to DC and DC to AC converter
Forced commutation required	not required	required
Losses	low	high
Power factor	low	high
Output frequency	can vary in steps	smooth control is possible
Number of devices	large	small
Applications	suitable for low speed range power drives	suitable for high frequency applications

Table 5-4 Comparision of cycloconverter and DC link converter[112]

Table 5-4 lists the differences between the cycloconverter and a DC link converter. As mentioned above, DC link converters are utilised with both FCSM as well as DFIM concepts, however the cycloconverter is used for the larger DFIM applications only.

[112] J. Anto @all- A Review of Power Electronic Converters for Variable Speed Pumped Storage Plants- 03/2018- IEEE JOURNAL of emerging and selected topics in power electronics Vol. 6,

5.5.3. Converter elements

Converter elements for self-guided power converters are:

- Bipolar transistor
- IGBT (Insulated gate bipolar transistor)
- IGCT (Insulated gate commutated transistor)
- GTO-Thyristor (Gate turn-off thyristor)
- Power-MOSFET (Metal oxide silicon field effect transistor)

The development of power transistors forced commutation became cost effective and enabled the widespread application of variable speed drives. Today, bipolar transistors have been replaced by IGBTs and IGCTs which simplifies the converter design and enables considerably higher switching frequencies. Since they are designed to turn on and off rapidly, they can synthesize complex waveforms with pulse-width modulation and low-pass filters.[113]

The IGBT is a voltage controlled device, hence it requires less gate drive power, thus simplifies the gate driver design. Due to the non-latched transistor operation, the IGBT has a shorter storage time, therefore pushes the IGBT to higher switching frequency. However, the large conduction voltage drop limits the popularity of IGBT at high voltages. Today, only 600A devices are available at 6.5 kV.

The state-of-the-art gate turn-off thyristor device capacity has reached nowadays up to 6000 V, 6000 A. However the GTO is hindered by its large storage time thus causing low switching frequency. Moreover it requires 1/3 or 1/5 of anode current to turn the device off.

IGCT devices use unity gain turnoff technique to cut the storage time of GTO by ten times, thus increasing the switching performance close to that of the IGBT. The low conduction loss and rugged structure make IGCT and power MOSFET more favourable than IGBT. The power MOSFET is a very fast switch, its switching speed is only limited by its capacity. Instead of the GTO it has no memory effect. The latest IGCT and power MOSFET devices have reached the same power level as a GTO.[114]

[113] Cf. Anders Carlsson- The back to back converter - control and design, 10/1998; Lund Institute of Technology

[114] Xigen Zhou@all - Comparison of High Power IGBT, IGCT and ETO for Pulse Applications, 2002

Table 5-5 lists the different converter elements with their specific characteristics.

Converter elements comparison table				
Device characteristic	**Power Bipolar**	**Power MOSFET**	**IGBT**	**IGCT**
Voltage rating	< 1 kV	< 4,5 kV	< 6 kV	< 6,5 kV
Current rating	< 500 A	< 4000 A	< 1,5 kA	< 5000A
Input drive	Current ratio h_{fe} 20…200 A	Voltage V_{GS} 3…10 V	Voltage V_{GE} 4…8 V	Voltage V_{GE} 4…8 V
Input impedance	Low	High	High	High
Output impedance	Low	Medium	Low	Low
Switching speed	Slow (µs)	Fast(ns)	Medium	Medium
Cost	Low	Medium	High	High

Table 5-5 Comparison of electronic devices[115]

[115] https://www.electronics-tutorials.ws/power/insulated-gate-bipolar-transistor.html

6. Comparison of variable speed concepts[116]

As we have discussed the characteristics, limitations and aspects of the various components as well as the available principles of speed regulation, the realised concepts should be discussed in this chapter.
A very important aspect which has not been addressed before is the cost aspect. When studying the literature, it turned out that depending on size of the hydro-electric power plant (HEPP), the different concepts have got their share in their market segment due to cost leadership. As we will discuss in due course the system investment costs after evaluation of technical or operational benefits are finally the drivers for the decision makers to decide on the final concept to be implemented. Based on aforesaid we can differentiate between the following types of variable speed generation system configurations:

Micro sized HEPP (less than approx. 100 kW unit output)

- Frequency converter with IM and DFIM
- Full scale frequency converter with SM

Small sized HEPP (approx. 100 kW...10 MW for axial type units and up to 25 MW for Francis & Pelton type units)

- Partial scale converter with DFIM
- Full scale converter with SM

Large HEPP (larger than small hydro)

- Partial scale converter with DFIM
- Full scale converter with SM

Different sized HEPP do have different characteristics, e.g. supply voltages.
There are various aspects to be considered when talking about selection of machine voltage.

- Optimum voltage means the voltage to achieve the best overall machine efficiency at a certain rating, winding design, construction type and speed
- Meeting the various standards of the generation and distribution customers (respectively derived national standards)

[116] Cf. Andritz Hydro-The generator for variable speed-01/2018

With regard to optimum voltage it can be stated that the design requirements respectively specification from the customers requires meeting the standard voltages in most cases which do not make optimum voltage design possible. These requests are due to the need of standardisation of other power equipment to enable redundancy of switchgear equipment and cost optimisation.

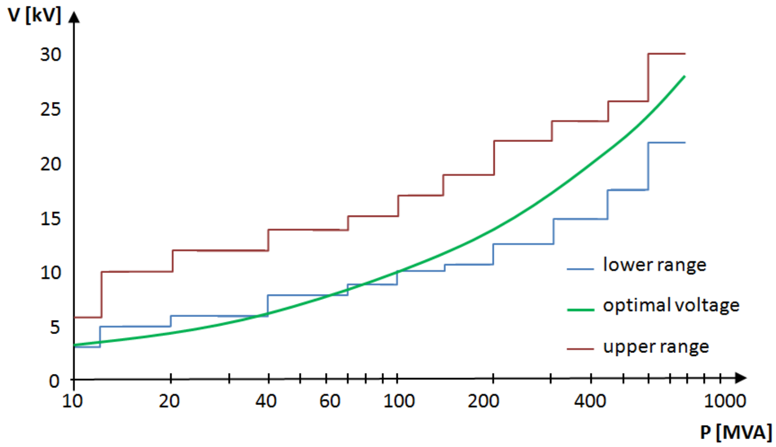


Figure 6-1 Line voltages[117]

As you can see from the figure above the typically requested voltage range is directly related to the machine rating. Particularly in the low capacity range the requested voltage is significantly higher than the optimum design voltage would be.

In the high capacity range customer tend more to voltage optimisation as they would then use e.g. switchgear equipment of the higher standard voltage category. In most cases these power stations have more than one unit therefore redundancy is not that critical or a spare transformer would be suitable for each of the units.

The following aspects are influencing the design of a DFIM and converter:

- Nominal and maximum output in motor and generator operation mode
- Minimum and maximum speed range in motor and generator operation mode
- Maximum possible clearances in rotor
- Available converter elements
- Maximum rotor voltage

Depending on the output and the speed range the converter can be sized. The rotor voltage is chosen in that way that on one hand the maximum creepage path and insulation clearances in the rotor can be kept, the sliprings can carry the rotor current and the rotor voltage makes a cost effective converter possible - number of

[117] Andritz Hydro-Generator voltage-2018

elements in series and in parallel, and the rotor current and voltage enable a suitable winding design.

Table 6-1 and Table 6-2 present the voltage ranges of the different sized HEPP for DC link converter and cycloconverter.

Type	Line voltage	DC link voltage	Stator voltage
Micro size HEPP	230...400 V	600...800 V	230...400 V
Small size HEPP	400...6300 V	0,8...10 kV	400...6300 V
Large size HEPP	10...21 kV	10...15kV	10...21 kV

Table 6-1 Voltage range of different sized HEPP with DC linked converter

Type	Stator voltage	Rotor voltage
Micro size HEPP	230...400 V	preferably 400 V but to be adopted to specific requirement
Small size HEPP	400...6300 V	3...6 kV
Large size HEPP	10...21 kV	3...6 kV

Table 6-2 Voltage range of different sized HEPP with cycloconverter

6.1 Micro size HEPP applications

Micro hydro-electric power plants are power plants with less than approx. 100 kW unit output. In this category two main configurations are dominating the market, therefore three-phase systems were considered only:

6.1.1 Frequency converter with IM and DFIM

The system consists of a squirrel cage asynchronous machine (SCIM) which is connected via a 4-quadrant frequency converter to the grid. The squirrel cage asynchronous machine is of a very robust design. A capacitor bank is foreseen for reactive power compensation of the converter (Figure 6-2). The reactive power control for the machine is powered by the intermediate circuit.

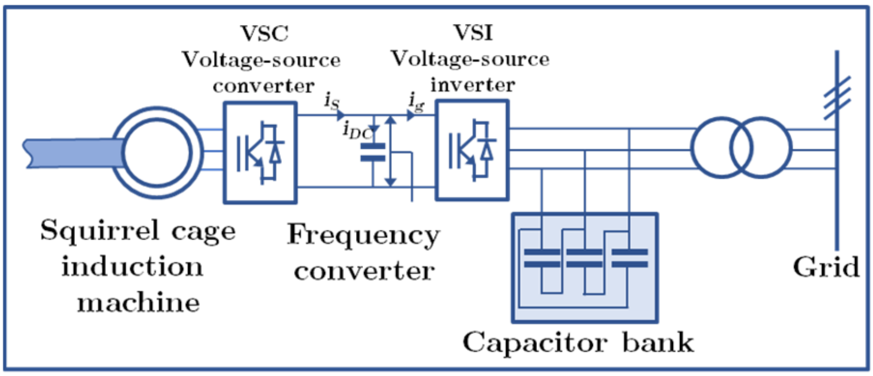


Figure 6-2 Squirrel cage induction machine (SCIM)

6.1.2 Full scale frequency converter with SM

This concept consists mostly of a permanent magnet synchronous machine (PMSM) which is connected through a full scale converter to the grid (Figure 6-3). Thus smallest machine sizes and very high machine efficiency are provided at all speeds. The PMSM is a preferable option in micro hydro due to its self-excitation property, which allows operation at high power factor.

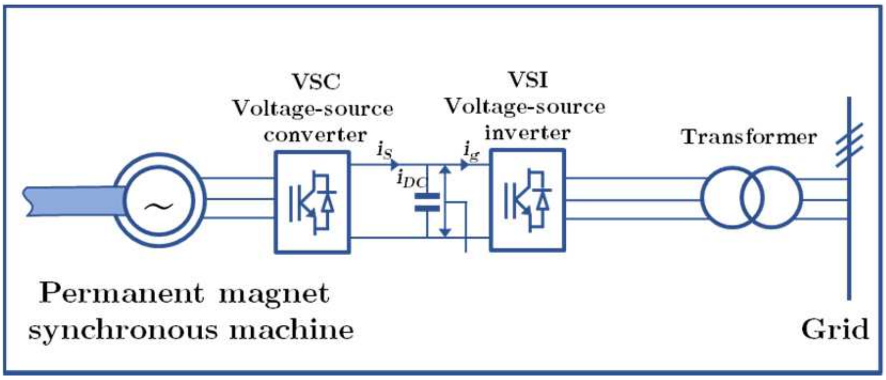


Figure 6-3 Permanent magnet synchronous generator (PMSG)

As the PMSM can easily be built to meet the turbine rated speed it can be directly coupled, not needing gearboxes, belts or other speed increaser systems. On the electric side, no excitation, no contactor etc. is required anymore. Contrarily it does not provide a constant voltage in particular with variable speed operation. Another disadvantage of PMSMs is that the magnetic materials are sensitive to higher temperature and overheating. Therefore, the rotor temperature of a PMSM must be supervised and a cooling system is required. But all in all, this concept is simple, very efficient and cost effective even for very small plant sizes.

6.2 Small sized HEPP

The next category is the small sized HEPP from approx. 100 kW up to approx. 10 MW for axial type units and up to approx. 25 MW for Francis & Pelton type units. In this category we see new concepts in the market which are not using a simple induction machine any longer.

6.2.1 Partial scale converter with DFIM

This concept takes advantage of the fact, that a doubly fed induction machine can be operated as very efficiency with variable speed by means of a converter connected to the rotor winding (Figure 6-4). The sizing of the converter in terms of active power must be only for the slip power and no more for the air-gap power. On the other hand, this converter has to provide the reactive power for the excitation of the DFIM as well as the reactive power of the stator in case of overexcited operational conditions. Usual slips are in the range of ± 15...20%, thus a significant saving on the converter size which usually overcompensates the more expensive rotor wound induction machine with slip rings.

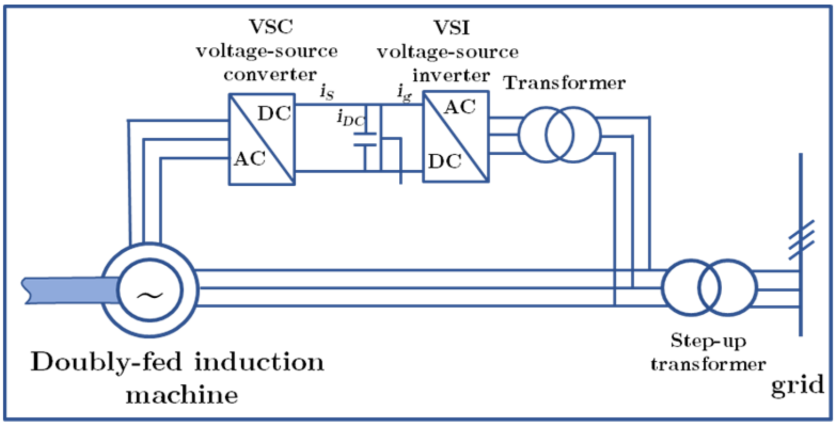


Figure 6-4 Doubly-fed induction machine (DFIM)

The stator voltage is applied from the directly connected grid and the rotor voltage is applied by the partial scale power converter consisting of two devices namely the rectifier part and the inverter. The stator feeds power into the grid all the time. The rotor, depending on the operating point, is feeding power into the grid when the slip is negative (super-synchronous operation) and absorbs power from the grid and from the stator when the slip is positive (sub-synchronous operation).

6.2.2 Full scale converter with SM

In this concept a synchronous machine (SM) is connected via a full scale power converter to the grid (Figure 6-5). Full scale power converter means that the stator of the machine is connected to the grid through a power converter. The amplitude and frequency of the voltage can be fully controlled by the power electronics at the machine side, so that the machine speed is fully controllable over a wide range, even to very low speeds.

The synchronous machine is usually equipped with permanent magnets. However, high power units are still built with a DC excitation on the rotor.

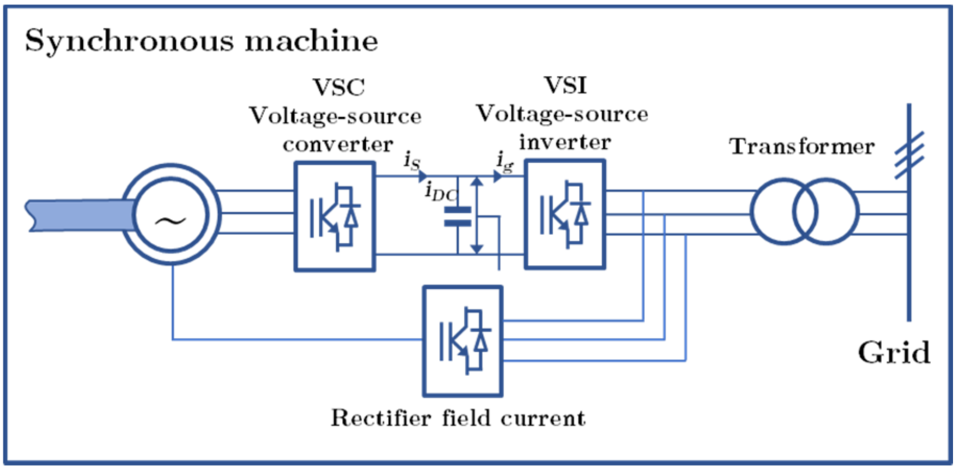


Figure 6-5 Synchronous machine (SM)

The main drawback of this concept is that the converter must be able to provide full power of the machine. As larger size converters are nowadays the breakthrough of this concept of the mentioned quite costly, another concept entered successfully the market.

6.3 Large HEPP

For large-sized hydroelectric power plant applications, the optimisation of the concepts becomes increasingly complex as investment costs, technical aspects (e.g. efficiency, cavitation) operational aspects (e.g. operation range, start-up as well as mode change duration) as well as maintenance aspects (cost and downtime) have to be carefully evaluated. Therefore, the following concepts are seen in the market:

6.3.1 Partial scale converter with DFIM

Generally speaking, a DFIM is the preferred solution for large unit outputs (more than 100 MVA). Its main advantage is that it requires only a low-size power converter compared to full machine capacity because it needs to handle the slip power only which usually is a small fraction of the total output. This means less power losses in the converters, lower total converter system cost and a much smaller space requirement for the power electronics.

The stator is directly connected via the station transformer to the grid. On the other hand the rotor is connected via the slip rings to a poly-phase symmetric AC system of variable frequency and amplitude, which is generated by the AC excitation system consisting of an appropriate converter as described below.

The system with a doubly fed asynchronous machine is fed on the rotor side either by a cycloconverter or by a PWM converter (Figure 6-6). This solution offers best dynamics and a large speed range.

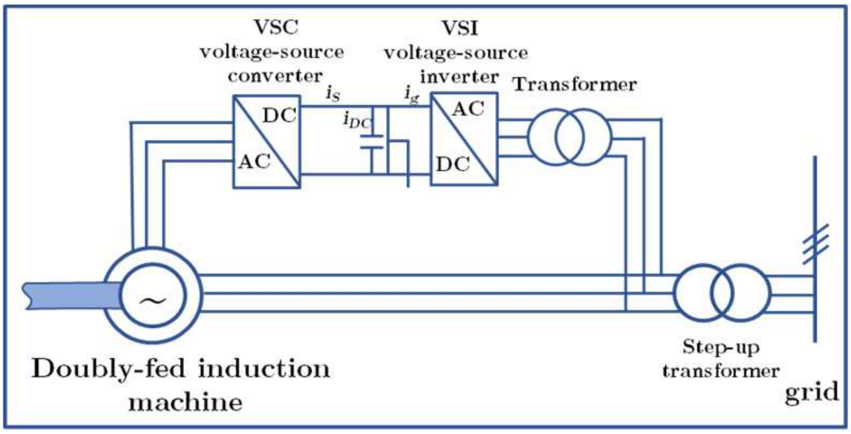


Figure 6-6 Doubly-fed induction machine (DFIM)

In reality all the large size pumped storage power plants such as e.g. Okawachi, Yagisawa, Kazunogawa, Goldisthal and Nant de Drance are equipped with DFIM.

6.3.2 Full scale converter with SM[118]

The system consists of a synchronous machine with a DC excitation connected to a full scale converter (Figure 6-7). Nowadays, the synchronous machine is usually of a salient pole type with a DC excitation. In the future, more and more permanent magnet excited machines will be used instead of the electric excited machines.

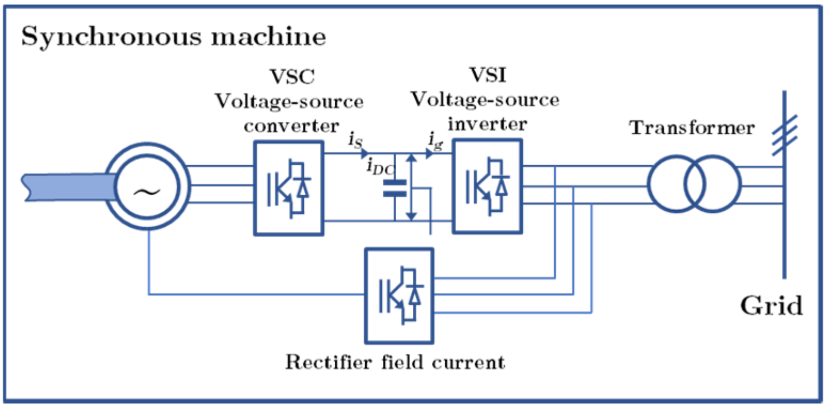


Figure 6-7 Full scale frequency converter

As the converter has to be dimensioned to carry full machine load, nowadays it is very costly. Recent studies have stated that the point of economy of a full scale converter is currently in the range of up to 75-100 MVA (Figure 6-8).[119]

[118] Cf. Anders Carlsson- The back to back converter - control and design, 10/1998; Lund Institute of Technology

[119] Richard K. Fisher@all: A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe

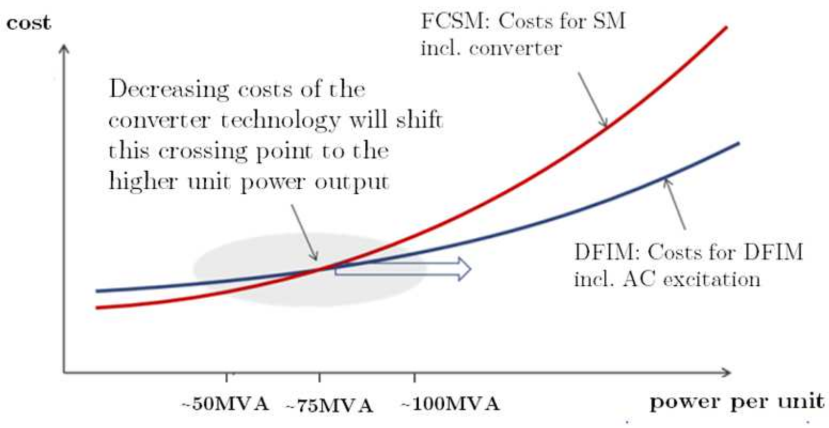


Figure 6-8 Indicative cost comparison for variable speed concepts[121]

The assets and drawbacks of a direct fed synchronous machine are listed below:

Advantages:

- The full scale converter can perform smooth grid connection over nearly the entire speed range
- Higher reliability due to the absence of mechanical components such as slip rings and brushes
- Very robust and reliable machine design due to mechanically and electrically simpler design, easy in maintenance
- Standard and cheap off-the shelf components available
- Need not to be synchronized to the electric system as e.g. a fixed speed synchronous machine
- Very fast start-up and mode changes of the unit, acceleration with almost rated torque from standstill to rated speed
- No time delay for synchronization due to permanent decoupling from the grid
- Easy speed reversal

Disadvantages:

- Higher cost and higher power losses in the power electronics, since all the generated power has to pass through two power converters
- Space and cooling requirement for the inverters
- Special design of winding insulation required for converter operation due to the higher dU/dt caused by the switching of the inverters

In Table 6-3 lists a comparison of fixed versus variable speed characteristics for a synchronous machine.

Feature	FIXED (synchronous machine)	VARIABLE (full-scale frequency converter)
Voltage and reactive power control	With automatic voltage regulation via variation of excitation current	With control of reactive current of the line side inverter (even at standstill).
Load control	By means of turbine governor	By means of turbine governor together with variation of speed to achieve most efficient system performance
Variation of grid frequency	Machine speed is limited by the allowed frequency range defined by grid code	Operation is possible in a wider frequency range via decoupling of the machine and grid by the converters
Voltage over frequency range	Limit values must be adhered to protect the machine	Due to decoupling via converters machine output voltage and grid parameters not restricted by machine
Voltage dips in grid	Time before unit trip due to stability reasons depends on remaining voltage, applied load and inertia of the unit	Due to decoupling via converters longer time before unit trips given. Reconnecting to grid without voltage and power oscillations. The rotor intermediate circuit can feed into the grid by reducing the intermediate circuit voltage.
Transient Stability	Power system stabilizer function optional (affects excitation current).	More easily stable operation due to decoupling of grid and generating unit.

Table 6-3 Comparison fixed vs. variable speed characteristics[120]

[120] G. Ciocan @all-Variable Speed pump-turbine technology UPB Scientific Bulletin-01/2012,

7. Overview of variable speed plants

Most commonly we think pumped storage technology is a modern technology developed in the 20th century. If we consider modern application of pumped storage for hydro-electric generation this is correct however the first applications of pumped storage go far back to the middle of the 19th century where windmills were used to pump water into an upper reservoir from where water mills were fed which drove mechanic driven weaving looms.[121] One of those was the 1863 commissioned PSPP Gattikon in Switzerland where in case of low water level when the flow of the river Sihl was not sufficient to drive the mill a Jonval turbine pumped 1 m^3/s from the river Sihl into an upper lake. Then the additional water from the lake was used to ensure sufficient hydro power to drive the mechanic driven weaving looms.[122]

Modern type pumped storage power plants were realised in 1884, 1891 and 1899 in Switzerland, later in the early 1920s, mainly in Italy, Austria, Germany and Switzerland. The installation of the first storage system for electricity in Germany was in 1923 when a PSPP with a capacity of 2.3 MW commenced operations in Hessen, Germany. The first configurations were equipped with separate turbine-generator and pump-motor sets using the same penstock. Later ternary solutions with turbine – motor/generator – pump all on one shaft were established. The first reversible pump-turbine was delivered by Voith in 1937 for the Pedreira power plant in Brazil.[123]

Also, in Japan and the USA from 1930 on pumped storage schemes were built. Until the 1970s the major task of pumped storage plants was to balance energy generation and consumption between day and night respectively within a week. Frequency control and grid balance was performed by other power plants. Only a few power plants in Europe did need pump capacity regulation and installed dual speed motor/generators with units able to operate with rotors changeable to two different number of pole pairs. As far as data were accessible, we talk about seven units in total with overall 280 MW installed capacity. Due to the inability of output regulation of fixed speed pump units, Japanese customers and manufacturers of electro-hydraulic equipment started to find ways to overcome this limitation.

With the aim of using pumping mode operation to perform supply and demand balancing during the night, Kansai Electric Power and Hitachi commenced the development of an adjustable speed pumped storage generation system in 1981. Following the commissioning in 1987 of a 17.5 MW demonstration plant that used adjustable speed generation system at the Kansai Electric Power's Narude power

[121] https://blog.zeit.de/schueler/2014/01/23/industrialisierung-geschichte-revolution

[122] https://energiespeicher.blogspot.com/2014/11/pumpspeicher-eine-alte-erfindung.html

[123] H. Bärtschi- Ein Pumpspeicherwerk von 1863- 06/2013

plant, two separate adjustable speed pumped storage generation systems with a world-largest capacity of 400 MW were commissioned by Hitachi in 1993 and 1995 respectively at the Kansai Electric Power's Okawachi power plant. Also Toshiba supplied at TEPCOs Yagisawa power station (Number 2, 80 MW), one unit with an adjustable speed pumped storage power generation system in 1990. Later in 2007, a 340 MW adjustable speed pumped storage generation system with the world's highest speed as of 576 to 624 rpm was commissioned at the Omarugawa power plant of the Kyushu Electric Power Co. Inc.[124,125]

But in the meantime, also in Europe variable speed has found its way to realisation. In 2004 the largest variable speed pumped storage scheme in Europe, Goldisthal in Germany, has been commissioned. In the last decade a number of variable speed systems were built or are still under construction worldwide, e.g. Forbach (EnBW, Germany), Avče (185 MW, Slovenia), Grimsel II (4x 93 MW, Switzerland) and Frades II (2x 390 MW, Portugal), Venda Nova III (2x 380 MW,Portugal), Nant de Drance (6x 175 MW, Switzerland), Linthal (4x 250 MW, Switzerland). In other parts of the world e.g. China (Feng Ning, 2x 360 MW), India (Tehri, 4 x250 MW) and Japan (Okukiyotsu 2, 600 MW; Kazunogawa 4, 400 MW; Shiobara 3, 300 MW) were built.[126]

Per mid 2019 we talk about 160 GW installed pumped storage capacity and more than 1000 units in operation worldwide. Total installed hydro-electric capacity installed worldwide and in operation is about 1,25 TW.[127] Due to the volatility of the increasing amount of renewable energy sources installed capacity additional capacity for grid balancing and frequency support will be required. As of today, pumped storage power plants are most convenient, fast reacting and a cost effective technology for energy storage and grid regulation support. With the increased capabilities of the variable speed units this technology seems to meet the needs of the grid operators nowadays and in the near future.

Table 7-1 lists the existing pumped storage power plant with dual speed and their characteristics e.g. number of poles, MW per unit and commissioning year. Table 7-2 instead lists the pumped storage power plants with variable speed with their total output, commissioning year, construction status and machine type.

124 https://www.hydro.org/wp-content/uploads/2017/08/PS-Wind-Integration-Final-Report-without-Exhibits-MWH-3.pdf

125 http://www.hitachi.com/rev/pdf/2010/r2010_03_107.pdf

126 https://energystorageexchange.org/projects

127 https://de.statista.com/statistik/daten/studie/468382/umfrage/installierte-leistung-von-wasserkraftanlagen-weltweit/

Title	Type	Qty	Unit MW	Two speed machine type	Number of poles 2p	Country	Commissioning
Hohenwarte	PHPS	2	20	unidirectional, pole changeable	44/36	Germany	1939
Ova Spin	PHPS	2	27	bidirectional, pole changeable	12/16	Switzerland	1965
Jukla	PHPS	1	48	bidirectional, pole changeable	12/16	Norway	1971
Malta Oberstufe	PHPS	2	70	unidirectional, pole changeable	12/16	Austria	1973

Table 7-1 Pumped storage hydro power plants dual speed[128]

Title	Type	Total GW	Machine type	Qty	Status	Country	Commissioning
Panjiakou	PHPS	0,09	FCSM	1	Operational	China	1989
Yagisawa	PHPS	80	DFIM	1	Operational	Japan	1990
Takami	PHPS	0,10	DFIM	1	Operational	Japan	1993/95
Okawachi	PHPS	800	DFIM	2	Operational	Japan	1993
Shiobara	PHPS	300	DFIM	1	Operational	Japan	1994
Okikuyotsu (Okukiyotsu) No. 2	PHPS	600	DFIM	1	Operational	Japan	1996
Goldisthal	PHPS	660	DFIM	2	Operational	Germany	2004
Avce	PHPS	185	DFIM	1	Operational	Slovenia	2010
Omarugawa	PHPS	300	DFIM	4	Operational	Japan	2011
Grimsel 2	PHPS	100	FCSM	1	Operational	Switzerland	2012
Kazunogawa (No.4)	PHPS	400	DFIM	1	Operational	Japan	2014
Frades II	PHPS	780	DFIM	2	Operational	Portugal	2016
Venda Nova III	PHPS	760	DFIM	2	Operational	Portugal	2016
Linthal (Linth-Limmern Expansion)	PHPS	1.000	DFIM	4	Operational	Switzerland	2016/17
Nant de Drance	PHPS	1.050	DFIM	6	Operational	Switzerland	2017
Okutataragi	PHPS	0,30	DFIM	1	Operational	Japan	2018/19
Tehri	PHPS	1.000	DFIM	4	Under Construction	India	2022
Feng Ning	PHPS	600	DFIM	2	Under Construction	China	2022
Compuerto	PHPS	0,01	DFIM	1	Operational	Spain	
Forbach	PHPS	270	DFIM	2	Under Construction	Germany	
Yanbaru	PHPS	0,03	DFIM	1	Operational	Japan	

Table 7-2 Large variable speed pumped storage hydro power plants[128,129]

legend

PHPS Pumped hydro power station

DFIM Doubly fed induction machine

FCSM Frequency converter fed synchronous machine

In the below sub-chapters 7.1 and 7.2 each one plant example for a DFIM and a FCSM configuration are presented in more detail.

[128] https://www.researchgate.net/publication/307641043_Global_distribution_of_grid_connected_electrical_energy_storage_systems/link/57db416c08ae5292a376a2c4/download

[129] https://www.researchgate.net/publication/307641043_Global_distribution_of_grid_connected_electrical_energy_storage_systems

7.1. Goldisthal

Goldisthal pumped storage plant (total 1120 MVA; 2x 261 MVA fixed speed and two times 300 MVA variable speed) on the Schwarza river is currently the largest hydro power plant with variable speed capacity located in Germany-Thuringia in Europe. Construction of the project began in September 1997, and the commissioning took place in October 2004. From the upper basin, the turbine has a volume of $13 \cdot 10^6$ m³ which means that all turbines can be operated at full load for eight hours. The upper basin is bordered by a ring dam with a total length of 3370 m.[130]

Upper basin
Net capacity $12 \cdot 10^6$ m³
Storage area 55 ha
Dam volume ~ $5{,}4 \cdot 10^6$ m³

Lower basin
Net capacity $19 \cdot 10^6$ m³
Storage area 78 ha
Dam volume $0{,}7 \cdot 10^6$ m³

Figure 7-1 Goldisthal area overview[131]

The Goldisthal pumped storage power plant is the first variable speed project with reversible pump-turbine of this size in a hydro power plant in Europe. It combines conventional pumped storage synchronous technology (represented by two single-speed motor/generators) and two units of variable speed DFIM technology (represented by two variable speed motor/generators). This arrangement, Figure 7-2 provides several benefits such as power regulation capability during pumping operation, improved efficiency at part load operation, and high dynamic control of the power delivered for stabilization of the grid (see chapter 5). The unit start-up time from standstill to full speed – full load is approx. 100 seconds.[130]

[130] C.f https://powerplants.vattenfall.com/de/goldisthal

[131] http://www.mgf-kulmbach.de/neu/index.php?option=com_content&view=article&id=591:exkursion-zum-pumpspeicherkraftwerk-goldisthal&catid=30&Itemid=334

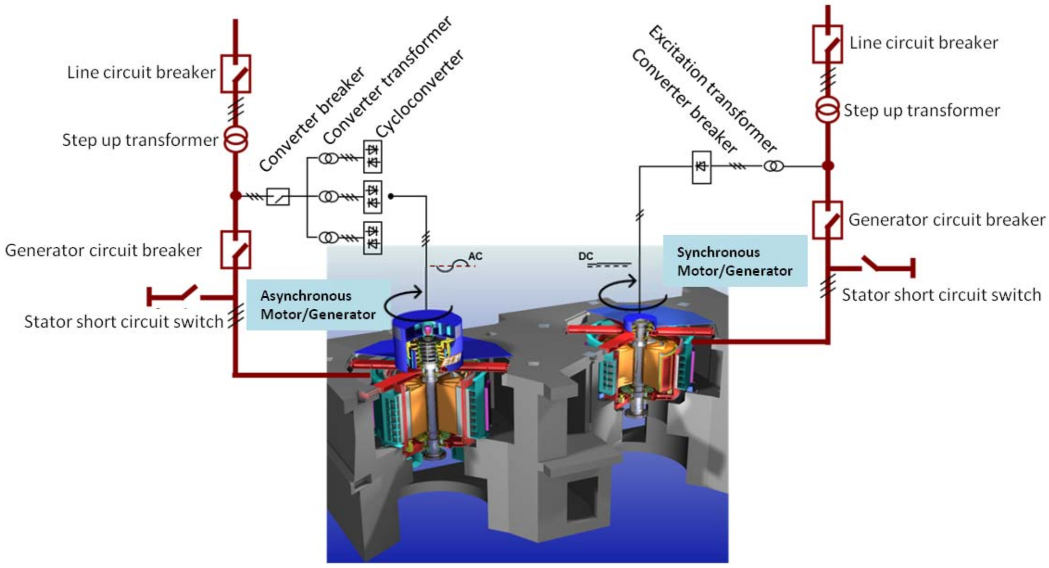


Figure 7-2 Principle electrical scheme of the pumped storage power plant Goldistahl[132]

The two classical synchronous machines are designed with salient pole rotors. They are energized by a converter driven with direct current excitation system to create the excitation field. The variable speed machine are equipped with a three-phase winding on the rotor instead and the rotor phases are energized by a low frequency alternating currents (AC) provided by a frequency converter. The frequency is related to the required speed. A direct frequency converter in the rotor circuit is used to control the frequency and therefore the speed of the units. The data of the Goldisthal pumped storage power plant is listed in Table 7-3.

	Asynchronous machine	Synchronous machine
Design Type	IM 8025 (W3)	IM 8025 (W3)
Motor	n= 300-346,6/min	
Nominal power [MW]	300	261
Nominal speed[$\frac{1}{min}$]	346,6	333,3
Efficiency cos φ	0,9 (grid)	0,8
Power grid[MW]	341,6	331
Efficiency [%]	97,59	98,57
Generator	n= 300-333,2/min	
Nominal power [MW]	311,8 (grid)	331
Nominal speed[$\frac{1}{min}$]	333,2	333,3
Efficiency cos φ	0,85 (grid)	0,8
Efficiency [%]	97,41	98,59

Table 7-3 Goldisthal pumped storage power plant data[132]

[132] Andritz Hydro- Pumped Storage Hydro Power Plant Goldisthal,07/17

Goldisthal is equipped with four reversible Francis pump-turbines (see Figure 7-3), two pump-turbines with variable speed and two with fixed speed. The data of those is listed in Table 7-4 and Table 7-5.

Figure 7-3 Pump-turbines of Goldisthal[133]

2 Pump turbines with variable speed			
Speed$[\frac{1}{min}]$	300	333,3	346,6
Pumping mode			
Head [m]	H_{min} = 280,49	H_{nom} = 306,74	H_{max} = 339,17
Flow rate $[\frac{m^3}{s}]$	Q = 57,68	Q = 80,00	Q = 80,63
Pumping power[MW]	P = 172,50	P = 257,4	P = 286,80
head (starting mode) [m]	H_0 = 375	H_0 = 460	H_0 = 500
Turbine mode			
Head[m]	H_{min} = 273,15	H_{nom} = 293,83	H_{max} = 330,40
Flow rate $[\frac{m^3}{s}]$	Q = 101,58	Q = 103,38	Q = 100,60
Turbine power[MW]	P = 244,90	P = 269,00	P = 300,00

Table 7-4 Goldisthal variable speed pump-turbines[133]

2 Pump turbines with fixed speed			
Speed$[\frac{1}{min}]$		333,33	
Pumping mode			
Head [m]	H_{min} = 282,23	H_{nom} = 306,74	H_{max} = 337,69
Flow rate $[\frac{m^3}{s}]$	Q = 88,34	Q = 80,00	Q = 68,10
Pumping power[MW]	P = 261,90	P = 257,00	P = 242,00
head (starting mode) [m]		H_0 = 460	
Turbine mode			
Head[m]	H_{min} = 273,63	H_{nom} = 293,83	H_{max} = 329,58
Flow rate $[\frac{m^3}{s}]$	Q = 98,27	Q = 103,33	Q = 111,42
Turbine power[MW]	P = 237,40	P = 269,00	P = 325,00

Table 7-5 Goldisthal fixed speed pump-turbines[133]

[133] Andritz Hydro- Pumped Storage Hydro Power Plant Goldisthal,07/17

Figure 7-4 Shaft of the DFIM Goldisthal[134]

Figure 7-5 Rotor of DFIM Goldisthal[135]

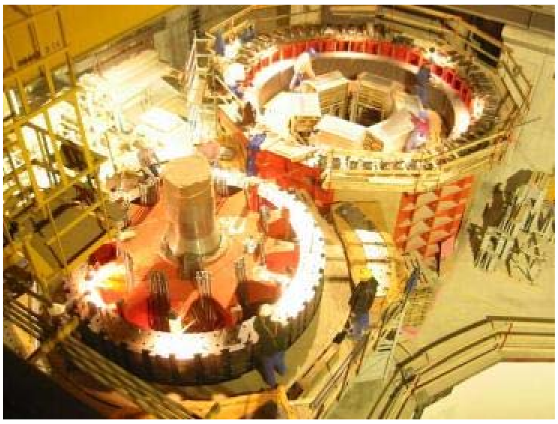


Figure 7-6 Machine units DFIM(left) and SM(right) of Goldisthal[135]

Figure 7-7 Trust bearing of Goldisthal[135]

The mass located in the overhang of the rotor windings has to be held by supporting elements against the centrifugal forces. In Goldisthal this is achieved by means of retaining rings made of non-magnetic steel.

Under the stress caused by the centrifugal force the radial elongation of the rotor rim made of electrical steel sheets and those of the retaining rings must be approximately the same in order to avoid additional stress in the rotor winding bars. The rim-duct rotor presses the cooling air in axial direction through the air ducts thus enabling the necessary heat transfer from the winding overhang and rotor pressure fingers.

The variable frequency current is fed into the rotor via sliprings. For the project Goldisthal the star point of the rotor is also connected to the neutral of the cycloconverter because of protection reasons, meaning that in Goldisthal we have DFIMs with 4 sliprings.

134 Andritz Hydro- Pumped Storage Hydro Power Plant Goldisthal,07/17

135 Andritz Hydro -Introduction of Goldisthal / Germany, 06/17

In Goldisthal a cycloconverter is equipped with two anti-parallel 12 pulse thyristor bridges per rotor phase, circulating currents, three parallel bridges (one for redundancy) and crowbars for protection (Figure 7-8). At a convenient converter, currents cannot be surely switched off, therefore circuit breakers are needed. After grid failure a restart has to be made, which reduces the overall availability. Therefore a new topology was equipped for drive through grid failure with a variable resistance. At normal operation mode the resistance is zero. During grid failure resistance leads into high value, which limits the mechanical stress of the machine. After grid failure the variable resistance returns in a small value, for maintaining drive in its speed range operation.

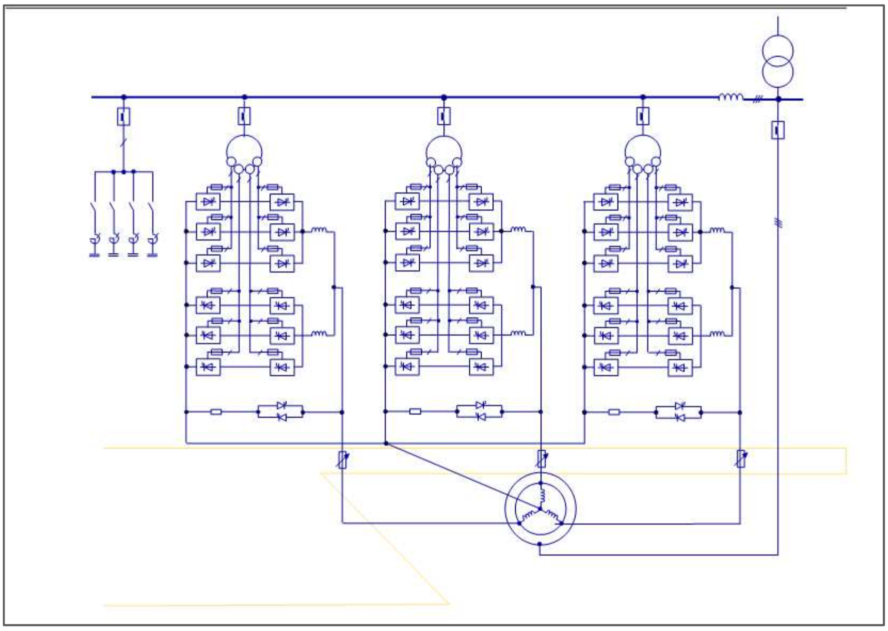


Figure 7-8 Cycloconverter of Goldisthal[136]

High efficiency results due to speed optimisation at partial loads and doubly fed design, while only 30 % of total power is fed by a converter. As well as a stabilisation of the grid is due to high-dynamic flux oriented control with a torque step in less than 10ms.

Figure 7-9 Asynchronous unit[137]

Figure 7-10 Synchronous unit[137]

[136] A.Bocquet-300MW umrichtergespeister drehzahlaribaler Antrieb für das Pumpspeicherkraftwerk Goldisthal-10/2005

[137] Andritz Hydro -Introduction of Goldisthal / Germany, 06/17

7.2. Grimsel II [138]

Grimsel 2 pumped storage power plant is one of the nine Oberhasli hydro-electric power company (KWO) power plants in Switzerland, which in total have an installed capacity of 1125 MW and generated annual energy of approx. 2200 GWh.
Figure 7-11 shows the complete hydraulic scheme of the KWO hydro-electric power system. Annual inflow amounts up to $700{\cdot}10^6$ m^3 and storage reservoir capacity totals $200{\cdot}10^6$ m^3.

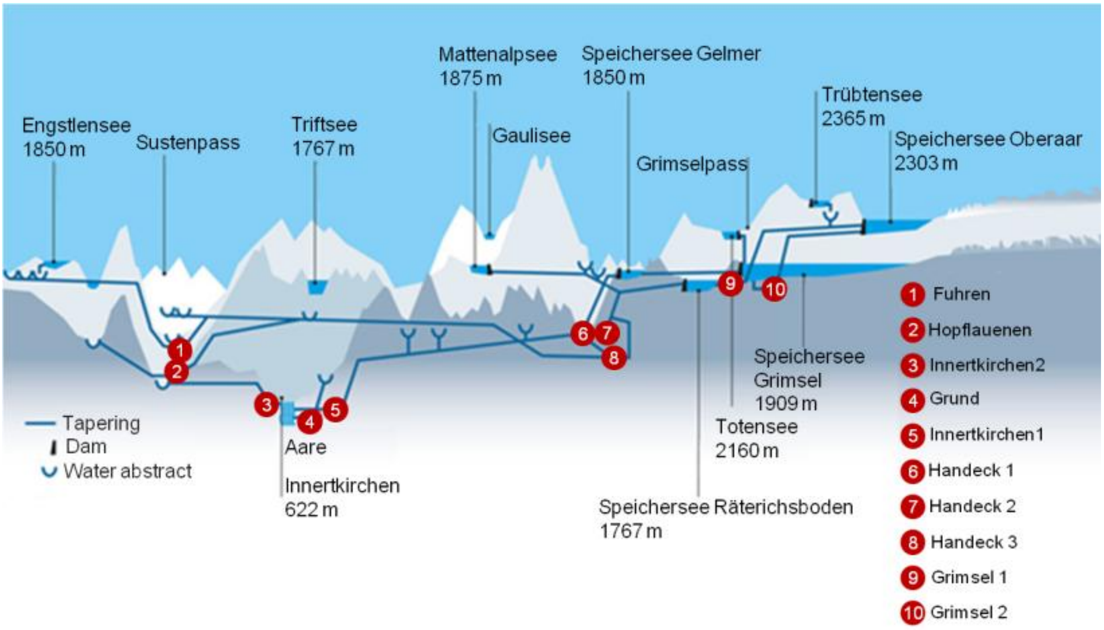


Figure 7-11 Oberhasli hydro-electric power system[139]

Grimsel 2 pumped storage power plant, was built between 1973 and 1980, it contains four 90 MW ternary machine sets. Each of them comprises of a horizontal-axis motor/generator, a Francis turbine and a pump. A renovation of all 4 machines was started in 2011 and one machine was equipped with the variable operation capability with the world's largest frequency converter (100 MVA) for a pumped storage power plant, which was finished in 2013.[140] During turbine operation the pump runner rotates in the dewatered housing, whereas during pump operation the turbine runner rotates in the dewatered housing. The turbine is used for starting both in pump and turbine operating modes. The main technical data of Grimsel 2 pumped storage plant are as follows (Table 7-6 and Table 7-7):

[138] H. Schlunegger and A. Thöni -100 MW full-size converter in the Grimsel 2 pumped-storage plant-11/2013

[139] C.f H.Schluegger @all- Kraftwerke Oberhasli AG Projekt «Varspeed» im Pumpspeicherwerk Grimsel 2, 09/18

[140] https://www.grimselhydro.ch/wp-content/uploads/fr__grimsel-2__generalrevision-mg1-4__2018-06-04.pdf

Grimsel 2	
Speed $[\frac{1}{\min}]$	750
4 Francis turbines	
Power[MW]	4 x 75
Flow rate $[\frac{m^3}{s}]$	93
Head [m]	400
4 Francis pumps	
Power [MW]	4 x 90
Flow rate $[\frac{m^3}{s}]$	80
Head [m]	400

Table 7-6 Grimsel 2 pumped storage power plant data[141]

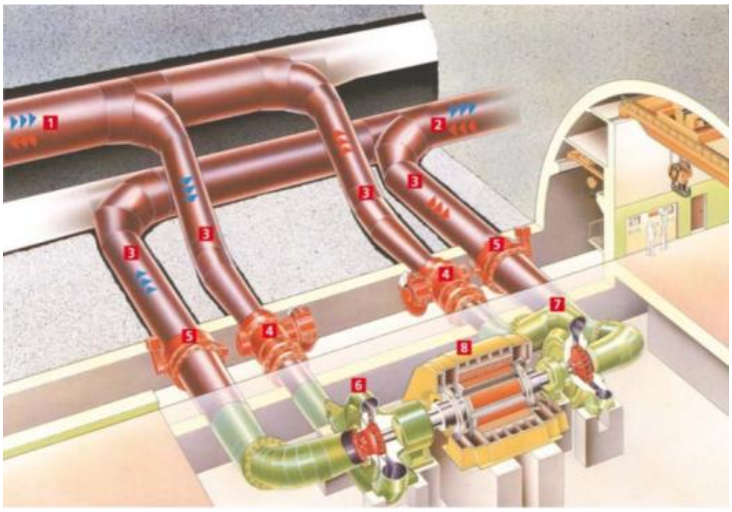
Grimsel 2 variable speed unit 2013	
1 Full-scale frequency converter[MVA]	100

Table 7-7 Grimsel 2 variable speed unit[141]

Grimsel 2 pumped storage power plant can be operating in the following modes:

- Turbine mode
- Pumping mode without converter (at constant speed)
- Pumping mode with converter (at variable speed)
- Synchronous condenser mode with converter (only reactive power, no active power)

Turbine operation with converter is not mentioned, because adjusting the Francis turbine speed to the relatively small head range would not compensate the converter losses.



1. high pressure shaft
2. low pressure shaft
3. manifold
4. butterfly valves
5. spherical valves
6. turbine
7. pump
8. motor/generator

Figure 7-12 Scheme of pumped storage power plant Grimsel 2[142]

[141] https://www.swv.ch/wp-content/uploads/2019/02/WEL_4_2017_Wem-geh%C3%B6rt.pdf

[142] H. Schlunegger and A. Thöni -100 MW full-size converter in the Grimsel 2 pumped-storage plant-11/2013

Figure 7-13 Frequency converter of Grimsel 2[143]

The converter is configured in two blocks on two floors, each with 50 MVA capacity and both are about 10 m wide and 7 m long at line and motor side, which include more than 1000 semiconductor elements. The semiconductors convert AC voltage from the power grid into DC voltage. The converter can store the DC voltage in the intermediate circuit for a short period and convert it then back into AC voltage with the desired frequency range as of 40 and 51 Hertz. The frequency depends on the speed of the pump which can be set with the converter in the range of 600 and 765 revolutions per minute.[144]

The respective block input and output voltages are added by the converter transformers at line and motor side. Each converter block comprises of double-phase modules made up of two three-phase three-level units in parallel. The converter system incorporates 24 double-phase modules in total (Figure 7-14).[145]

143 https://www.maschinenmarkt.ch/index.cfm?pid=8787&pk=420899&fk=633924&type=article

144 https://library.e.abb.com/public/0ee456abcf33cf89c1257d6900347076/Reference_Grimsel_RevA.pdf

145 Cf. https://www.jungfrauzeitung.ch/artikel/127239/

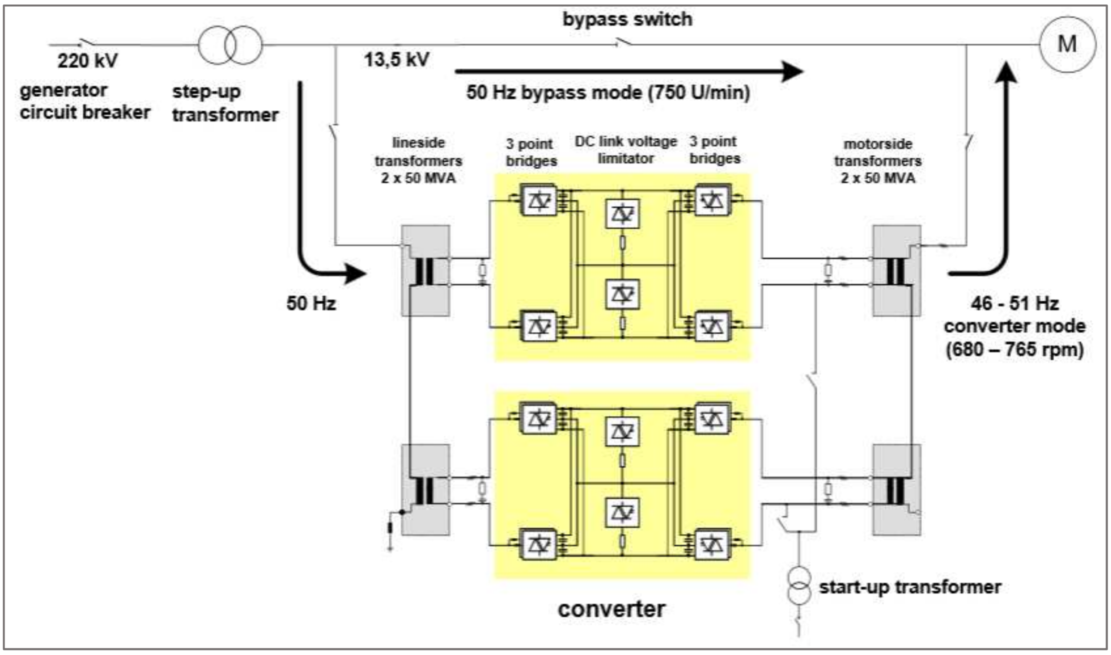


Figure 7-14 Single line diagram of the frequency full scale converter of Grimsel 2[146]

The pump can be operated over a wide power range from 60 to 100 MW. The minimum power is defined by the pump cavitation limit, the maximum power by the frequency converter capacity and admissible torque of the pump shaft.

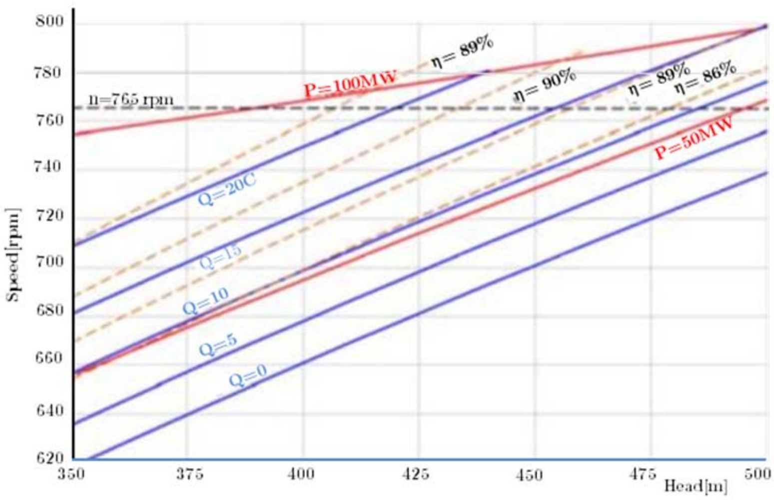


Figure 7-15 Pump characteristics of Grimsel 2[146]

To start-up the machine set in turbine mode as well as in unregulated pumping mode, the turbine is always used. The step-up transformer is magnetized by the machine and connected to the 220 kV level after reaching synchronization conditions. In regulated pumping mode instead, the step-up transformer and the two line-side converter transformers have to be directly connected, which causes very high inrush current peaks. To avoid this, the frequency converter DC link is energized by the start-up transformer through the converter diodes on the motor side. The transformers are then

[146] H. Schlunegger and A. Thöni -100 MW full-size converter in the Grimsel 2 pumped-storage plant-11/2013

magnetized by the line-side converter and afterwards synchronized. The entire starting procedure takes only about 10 seconds, after which the machine is accelerated by the converter to 600 rpm with the watered pump operating against the closed spherical valve. After opening the spherical valve, the speed is according to the minimum power required by the current operating head.[147]

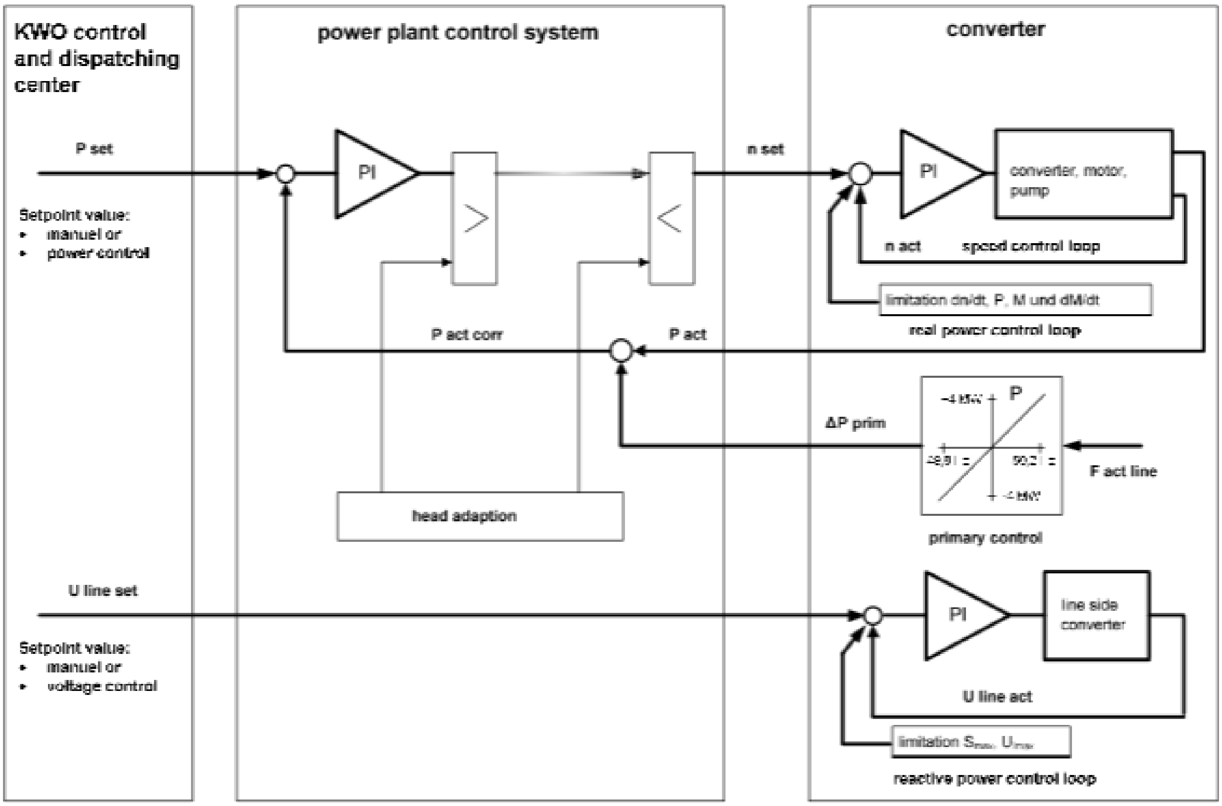


Figure 7-16 Converter control loops of Grimsel 2[146]

Figure 7-16 shows the implemented power plant control philosophy, necessary to integrate the variable speed unit according to the grid respectively dispatch centre requirements.

[147] H. Schlunegger and A. Thöni -100 MW full-size converter in the Grimsel 2 pumped-storage plant-11/2013

8. Conclusion

In the presented work, variable speed concepts of hydro power plants, mainly used at pumped storage power plants are shown.

An overview about the electric power generation and its task and needs, is presented. Hence to the high amount of volatile renewable energy sources in the grid, the requirements for power plants have been changed significantly. Quick responses to changing electric power demand with a high efficiency are needed.

Per mid 2019 we talk about 160 GW installed pumped storage capacity and more than 1000 units in operation worldwide. Total installed hydro-electric capacity installed worldwide and in operation is about 1250 GW. As of today pumped storage power plants are most convenient, fast reacting and a cost-effective technology for energy storage and grid regulation support. With the increased capabilities of variable speed units, this technology seems to be meeting the needs of the grid operators nowadays and also in the mid-term future.

Pumped storage hydro power plants with the variable speed technology are able to meet the increasing requirements of the grid. Variable speed units are able to react to such disturbances by adapting the speed to the new power requirements and compensate the energy (absorb or release) in the inertia of the hydraulic system.

Running the unit at different speeds the turbine can be operated at the optimum efficiency point for the actual hydraulic parameters. During dynamic grid operation it is necessary to inject or absorb active power from the grid within a short reaction time.

In pump mode at fixed speed operation power regulation is not possible due to the given system parameters namely hydraulic head and mass flow. At variable speed at maximum hydraulic head where the machine comes close to the suction side cavitation limit, the speed can be reduced to achieve pump inflow angles which better correspond to the geometry of the runner blades. Vice versa at minimum hydraulic head, the speed can be increased to avoid pressure side cavitation and to extend the operating range to a larger flow. Furthermore, at variable speed the absorbed motor power can be controlled in a wide range with rather small speed changes, enabling adjustment of power consumption to support grid stability in case of existing over- or under-capacity.

In particular for the large power range, currently two technologies are competing at the marketplace in terms of variable speed motor/generators, namely the doubly fed induction machine with an inverter on the rotor side and the synchronous machine with a full scale inverter on the stator side with conventional DC-excitation. The decision which one is used is driven by operational requirements as well as economic factors. Currently the full scale inverter on the stator side concept is mainly selected for units less than 75...100 MVA whereas the doubly fed induction machine is selected for unit sizes greater than 100 MVA due to lower investment costs. As it can be expected that the cost development of semiconductor technology will make bigger ratings of converters also feasible in the near future, the above mentioned threshold may be shifted to larger MVA ratings.

Although the doubly fed asynchronous machine concept is the by far the most realised concept in large (larger than 10 MVA) hydro units, with the developments of the converter technology on-going decrease of specific costs other concepts will be realised. Particularly for micro (lower 100 kVA) to small (from 100 kVA up to 10 MVA) sized hydro units with an electric or permanent magnet excited synchronous machine fed with variable frequency by a full scale converter will be implemented.

On the other hand, for smaller sizes synchronous machines with permanent magnets in the rotor could be used for variable speed instead of an asynchronous machine eliminating certain disadvantages of a squirrel cage induction machine. Permanent magnet machines are rarely used today but in the upcoming future more and more permanent magnet excited machines will be used instead of electric excited machines.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass die vorliegende Arbeit nach den anerkannten Grundsätzen für wissenschaftliche Abhandlungen von mir selbstständig erstellt wurde. Alle verwendeten Hilfsmittel, insbesondere die zugrunde gelegte Literatur, sind in dieser Arbeit genannt und aufgelistet. Die aus den Quellen wörtlich entnommenen Stellen, sind als solche kenntlich gemacht.

Das Thema dieser Arbeit wurde von mir bisher weder im In- noch Ausland einer Beurteilerin/einem Beurteiler zur Begutachtung in irgendeiner Form als Prüfungsarbeit vorgelegt. Diese Arbeit stimmt mit der von den Begutachterinnen/Begutachtern beurteilten Arbeit überein.

Wien, im Jänner 2020