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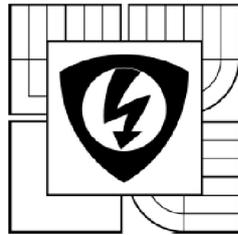
## **SUPER GRIDS CONCEPTION**

**BAKALÁŘSKÁ PRÁCE  
BACHELOR'S THESIS**

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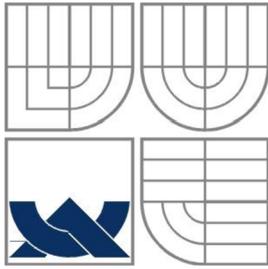
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**BRNO UNIVERSITY OF TECHNOLOGY**



**Faculty of Electrical Engineering and Communication**  
**Department of Electrical Power Engineering**

**Bachelor's Thesis**

# **Super Grids Conception**

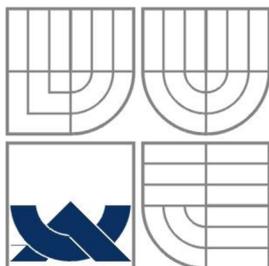
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**Brno University of Technology, 2012**

**Brno**



**VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ**



**Fakulta elektrotechniky a komunikačních technologií**  
**Ústav elektroenergetiky**

**Bakalářská práce**

# **Koncepce Super Gridů**

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**Ústav elektroenergetiky, FEKT VUT v Brně, 2012**

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## ABSTRACT

The aim of bachelor's thesis "Super Grids Conception" is to provide complex overview of Super Grids topic in terms of describing the background, concept itself, available technology, experience and further development, possible energy sources and particular concepts and studies.

In the beginning, reasons which lead to need of next-gen electrical grids are identified in global goal to reduce environmental impact of power generation, growing electricity demand and emerging need to integrate renewable energy sources. Possible energy sources of the future are discussed in broader context as well as in sense of current limitations and further development.

In second part, concepts of Smart Grids, Super Grids and SuperSmart Grids are described focusing on benefits, basic principles and systemic point of view.

The author then elaborates on Super Grids Conception. HVDC and HVAC technologies are compared from technical and economical point of view, resulting typical usage is mentioned. Later a detailed overview of state-of-the-art HVDC systems technology is provided, including basic principles and design, components description, limitations of available technology, practical experience and possible development areas. Challenges in HVAC field towards Super Grids are introduced, as well as the issues related to hybrid AC/DC corridors and lines. In the last part, differences in historical development and present attitude between different parts of the world are explained. Considered Super Grid conceptions are introduced with special aim to visionary DESERTEC Foundation Concept and techno-economic study OffshoreGrid.

**KEY WORDS:** Super Grids; Smart Grids; HVDC; HVAC; electricity transmission; electrical grid; energy sources; renewable energy

## ABSTRAKT

Cílem bakalářské práce “Super Grids Conception” je poskytnout komplexní náhled na problematiku Super Gridů ve smyslu pozadí, konceptu jako takového, dostupných technologií, dosavadních zkušeností a budoucího vývoje, možných zdrojů elektrické energie a konkrétních konceptů a studií.

V úvodu jsou osvětleny důvody vedoucí k potřebě elektrických sítí nové generace – celosvětové snahy snižovat dopad výroby elektrické energie na životní prostředí, rostoucí poptávka po elektrické energii a potřeba integrovat obnovitelné zdroje energie. Možné zdroje elektrické energie jsou diskutovány jak v širším kontextu, tak i ve smyslu současných omezení a budoucího vývoje.

V druhé části jsou popsány koncepty Smart Gridu, Super Gridu a SuperSmart Gridu s důrazem na přínosy, základní principy a systémové hledisko.

Autor se dále zabývá jen koncepcí Super Gridu. Použití stejnosměrných (HVDC) a střídavých (HVAC) technologií je porovnáno z technického i ekonomického hlediska a z něj vycházející typické použití těchto technologií. Dále je podrobně popsána nejlepší dostupná technologie HVDC systémů – základní principy a konfigurace, popis jednotlivých částí, omezení současných technologií, dosavadní zkušenosti a možný prostor pro další vývoj. Následuje zmínka nových výzev oblasti HVAC technologií ve vztahu k Super Gridům a popis problémů souvisejících s hybridními AC/DC linkami a koridory. V poslední části jsou vysvětleny rozdíly v historickém vývoji a současných postojích v různých částech světa. Zároveň jsou představeny koncepce zvažovaných Super Gridů. Zvláštní prostor je poskytnut vizionářské koncepci vytvořené DESERTEC Foundation a technickoekonomické studii OffshoreGrid.

**KLÍČOVÁ SLOVA:** Super Gridy; Smart Gridy; HVDC; HVAC; přenos elektřiny; elektrická síť; zdroje energie; obnovitelná energie

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## SYMBOLS AND ABBREVIATIONS

AC	Alternating Current	
<i>B</i>	capacitive susceptance	S
BWGR	Boiling light-water-cooled, graphite-moderated reactor	
CCC	Capacitor-Commutated Converter	
CCGT	Combined Cycle Gas Turbine	
CCPP	Combined Cycle Power Plant	
CCS	Carbon Capture and Storage	
CSC	Current Source Converter	
CSP	Concentrating Solar Power	
DC	Direct Current	
DNI	Direct Normal Insolation	
EGM	Electro-Geometric Method	
EHVAC	Extra High-Voltage Alternating Current	
EHVDC	Extra High-Voltage Direct Current	
EU ETS	The European Union Emission Trading System	
FACTS	Flexible Alternating Current Transmission System	
FBR	Fast Breeder Reactor	
FSC	Fixed Series Capacitor	
GTO	Gate Turn-Off Thyristor	
HRGS	Heat Recovery Steam Generator	
HVAC	High-Voltage Alternating Current	
HVDC	High-Voltage Direct Current	
IEA	International Energy Agency	
IGBT	Insulated-Gate Bipolar Transistor	
IGCT	Integrated Gate-Commutated Thyristor	
ITER	International Thermonuclear Experimental Reactor	
LFR	Linear Fresner Reflector	
MMC	Modular Multilevel Converter	
MSC	Mechanically Switched Capacitor	

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MSR	Mechanically Switched Reactor	
OCT	Optical Current Transformer	
OH line	Overhead line	
OVT	Optical Voltage Transformer	
PWM	Pulse Width Modulation	
PWR	Pressurized light-water-moderated and cooled reactor	
SNG	Substitute Natural Gas	
STATCOM	Static Compensator	
SVC	Static VAR Compensator	
TCSC	Thyristor Controlled Series Capacitor	
TPSC	Thyristor Protected Series Capacitor	
UHVAC	Ultra High-Voltage Alternating Current	
UHVDC	Ultra High-Voltage Direct Current	
$U_{PP}$	Voltage – peak to peak value	V
$U_{RMS}$	Voltage – root mean square value	V
VSC	Voltage Source Converter	
$X$	inductive reactance	$\Omega$
$Y$	Transversal admittance	S
$Z$	Longitudinal impedance	$\Omega$

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# 1 INTRODUCTION

## 1.1 Background

The modern world faces various problems – poverty, terrorism, AIDS or most recently economic depression. One of the most discussed and concerning problem is **securing energy supply without a significant ecological trace**. No wonder, this issue touches developed countries directly, unlike poverty for example, threatening the very base of economics and day-to-day life. Additionally, developed countries are undoubtedly the biggest consumers (and producers, of course) of electricity, or energy in general, therefore their actions in this field have the potential of global effect in various ways – air pollution, acid rains, climate change, nuclear waste, etc. The problem is intensified by massive growth of energy demand in south-east Asia, which is caused by slowing population growth and hastily rising level of living in the region, and is unlikely to stop in the near future. Furthermore, population growth and economy development is expected in Africa in the upcoming decades.

According to statistics of International Energy Agency [1], roughly 2/3 world's electricity production came from fossil fuels in 2008, and it is not anticipated that these numbers have changed significantly. And as it is known, burning fossil fuels goes hand in hand with emissions. Firstly research showed negative effects of fly-ash, and fly-ash separation systems were installed. Later scientists proved unpropitious impact of nitrogen and sulphur oxides on environment, and utilities were obliged to apply nitrogen and sulphur oxides capture systems. Today's biggest concern is carbon dioxide and its potential to change global climate.

This topic will not be elaborated further, as it is kind of a “hot button”, and many contradictory papers have been published in last decades. It is, however, convenient to mention one particular fact – atmospheric **concentration of carbon dioxide is abnormally high and rapidly growing**, as graphs at Figures 1 to 3 show. Whether it causes global warming or not and whether it is good thing or not, lowering carbon dioxide emissions has been set as a global goal. Achieving this goal while keeping electricity supply stable and reasonably priced is a serious engineering challenge. As the problem is very complex, local condition various and effects on environment unproved, yet potentially catastrophic and irreversible, there is no clear and simple way we, as a civilization, should take. However there are ideas of possible solutions. Some of them are bold and confronting lot of practical problems, like for example using photovoltaic panels as a road surface [2], some are already successfully in usage, such as nuclear and hydro power plants.

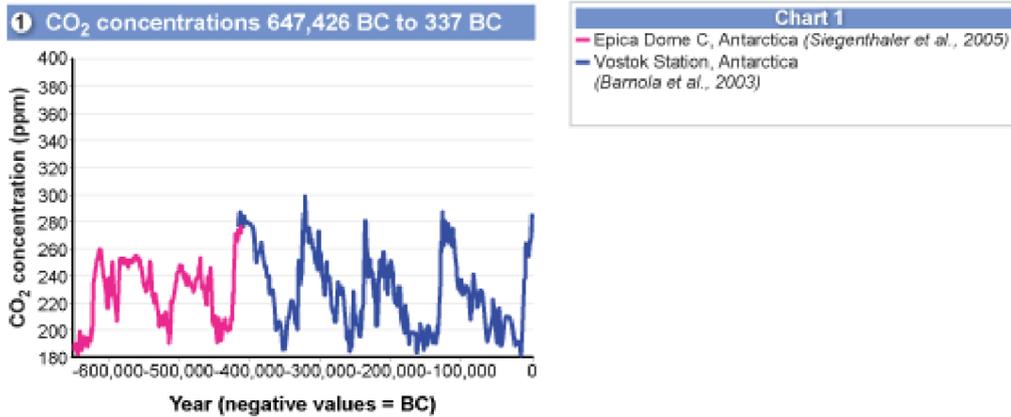


Figure 1 – Atmospheric concentrations of carbon dioxide 647426BC to 337 BC [74]

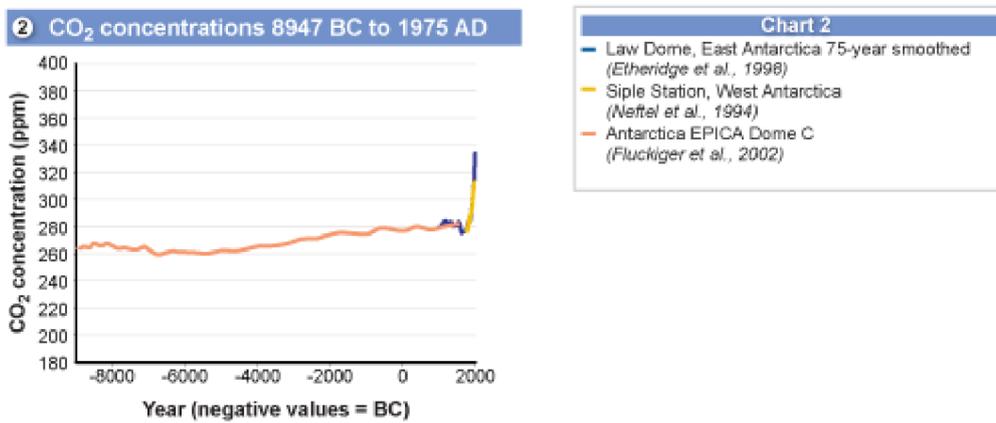


Figure 2 – Atmospheric concentrations of carbon dioxide 8947 BC to 1975 AD [74]

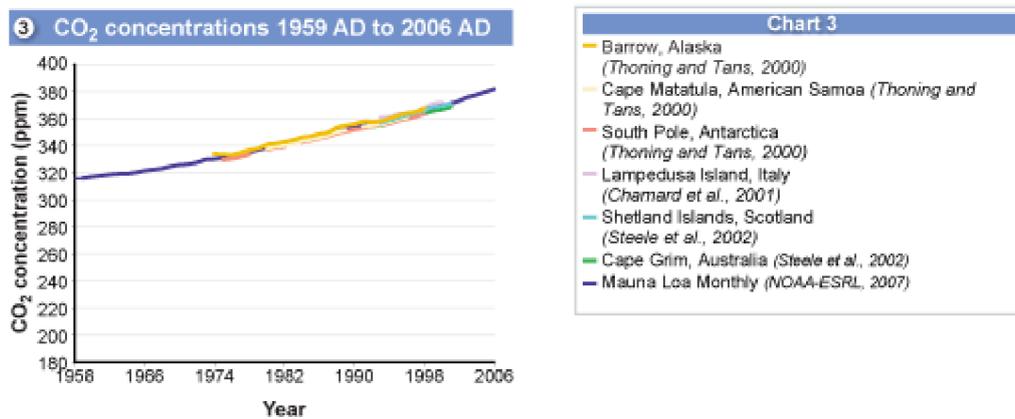


Figure 3 – Atmospheric concentrations of carbon dioxide 1959 to 2006 [74]

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## 1.2 “New” energy sources

### 1.2.1 Renewable energy sources

At the moment there is disparate spectrum of possible replacements for fossil fuels. Nowadays renewable energy sources are very popular. According to International Energy Agency [1], in 2008 18.7 % of total 20,181 TWh of electricity was produced by renewable energy sources.

Most common are **hydropower** plants with 15.9 % share on aggregate production. Unfortunately most of the hydropower potential for projects above 1 MW has been in developed countries already utilized. However, there is still a lot of available capacity for small and micro hydro power plants. This indicates possible massive growth in the future in cooperation with Smart Grids. On the other hand large-scale project especially in Asia and South America can benefit from HVDC (High-Voltage Direct Current) transmission and play a key role in covering rapidly growing electricity demand. **Pumped-storage hydropower** plants are gaining high importance in modern transmission system, especially with massive renewable energy sources deployment, as they provide currently the only efficient and affordable possibility of energy storage.

Other commonly used renewable energy sources are **wind energy and photovoltaic**. They have, however, a few disadvantages. Firstly, plant's power strongly depends on weather – to be more accurate – power is limited by strength of sunlight or wind. Additionally if the wind is too strong the plant shuts down automatically for security reasons. Secondly these power plants have limited possibilities of power regulation; older plants are not even equipped with any power regulation at all. Therefore to predict plant's power, a very accurate weather forecast for particular location is needed. Forecast of course cannot be always 100% accurate, which leads to stressing the grid and other power generating units. Due to uncertainty of delivered power these sources still have to be backed up by conventional sources with high output power flexibility. The problem is intensified especially in developed countries by current legislative obligating distributor to buy electricity from wind and solar power plants, additionally for subsidized prices. It doesn't require lot of research to realize that this approach is from technical and economical point of view inconvenient. There is no room for massive usage of weather-dependent sources in conventional grids as they cause destabilization of the grid. As deterrent example let be mentioned Germany, which is destabilizing this way not only its own grid, but also systems of neighbouring countries, and still have to keep conventional sources as a backup. However, in the grids of the future usage of wind power and photovoltaic is very likely. Small units will play an important role in Smart Grids, while powerful wind parks are essential for robust Super Grid.

Closer look to **biomass** power plants and the way the whole system operates, leads to an unfavourable conclusion - the system definitely emits additional carbon dioxide. How is then possible, that it has been generally presented the opposite in last decade? The answer is very simple; the calculations often leave out of consideration gaining, transportation

and processing of the combusting material. Although biomass power plants are a good way for waste processing, it is highly inappropriate to use agriculture areas for purpose of growing fuel in order to act ecologically. Firstly, as mentioned above, the system produces emissions. Secondly, arable land is destined for agriculture purposes – growing agriculture plants or grazing. Switching to energy purposes leads globally to insufficient supply on commodity market and therefore growth of prices. This indirectly means increasing poverty rate and famine. On local level it leads to increasing need of importing agriculture products, which produces even more emissions, not to mention lower quality of imported commodities and products.

Potentially very competitive (especially as a part of a Super Grid), yet still not widely deployed are **Concentrating Solar Power** plants (CSP). There are 4 main technologies:

- Parabolic Trough systems use curved mirrors to concentrate solar power to steel absorber tubes filled with liquid, typically synthetic oil. Each row of mirrors is equipped with one absorber. The oil heated in such array is then used in heat exchanger to produce steam, which is used to drive conventional steam turbine.
- Linear Fresner Reflectors (LFRs) also use mirrors and absorber tubes. The mirrors are flat or just slightly bent and more rows of mirrors reflect light to one absorber. This design leads to reduced investment costs and possibility to use direct steam generation instead of heat exchanger with vaporizer.
- Solar Towers, also known as Central Receiver systems, use group of heliostats (individually continuously adjusting mirrors) to focus solar energy to a certain point – the top of the tower, where the working fluid could be heated to more than 1000 °C and used for electricity generation conventionally.
- Parabolic dishes focus energy to a certain point. However, the point is not common for all dishes; every dish has its own absorber and small Stirling engine or gas turbine of tenths of kilowatts. Parabolic dishes can be successfully used in small-scale plants, for large-scale projects mass production is required.

Each technology has pros and cons. Design of Parabolic Troughs is considered to be the most advanced, plants were built since 1984 mainly in Mojave Desert in California and are commercially proven. LFR plants require much lower investment costs. Large-scale Solar Towers achieve better efficiency using high temperatures in Rankine cycle, while parabolic dishes offer modularity, possible mass production, high efficiency and don't need cooling.

CSP plants currently provide total installed power of 1 GW, another 15 GW is planned or under construction. The solar energy in CSP plants faces the same problem as in photovoltaic plants – immediate power is limited by sunlight. However, unlike photovoltaic, CSP offers possibility of thermal power storage and fossil fuel back-up to cover sudden decrease of sunlight intensity and to enable operation even few hours after sunset. High DNI (Direct Normal Insolation) required for a profitable CSP plant is typically available in distant arid areas. This fact brings out two issues – power transmission and cooling. Losses of power transmission can be reduced using HVDC technology. However, water consumption for

cooling is causing problems in arid areas. Usage of dry cooling causes power penalty of 7 %. The main barriers of CSP deployment are high investment costs and high price per generated MWh. The investment costs are €3.5 - €6.5 per watt; that means comparable with nuclear power. The capacity factor of CSP plants ranges from 25 % with typical usage to 35 % using combined cycles and, comparing to conventional fossil fuel-fired and nuclear power plants, which reach capacity factor of up to 92 %. Therefore CSP are not capable to reach average market price €50 per MWh without subsidizing. Current levelised energy price is around €160 - €240 per MWh, reaching competitive peak-load price is not expected before 2015, base-load price not until 2030 [3].

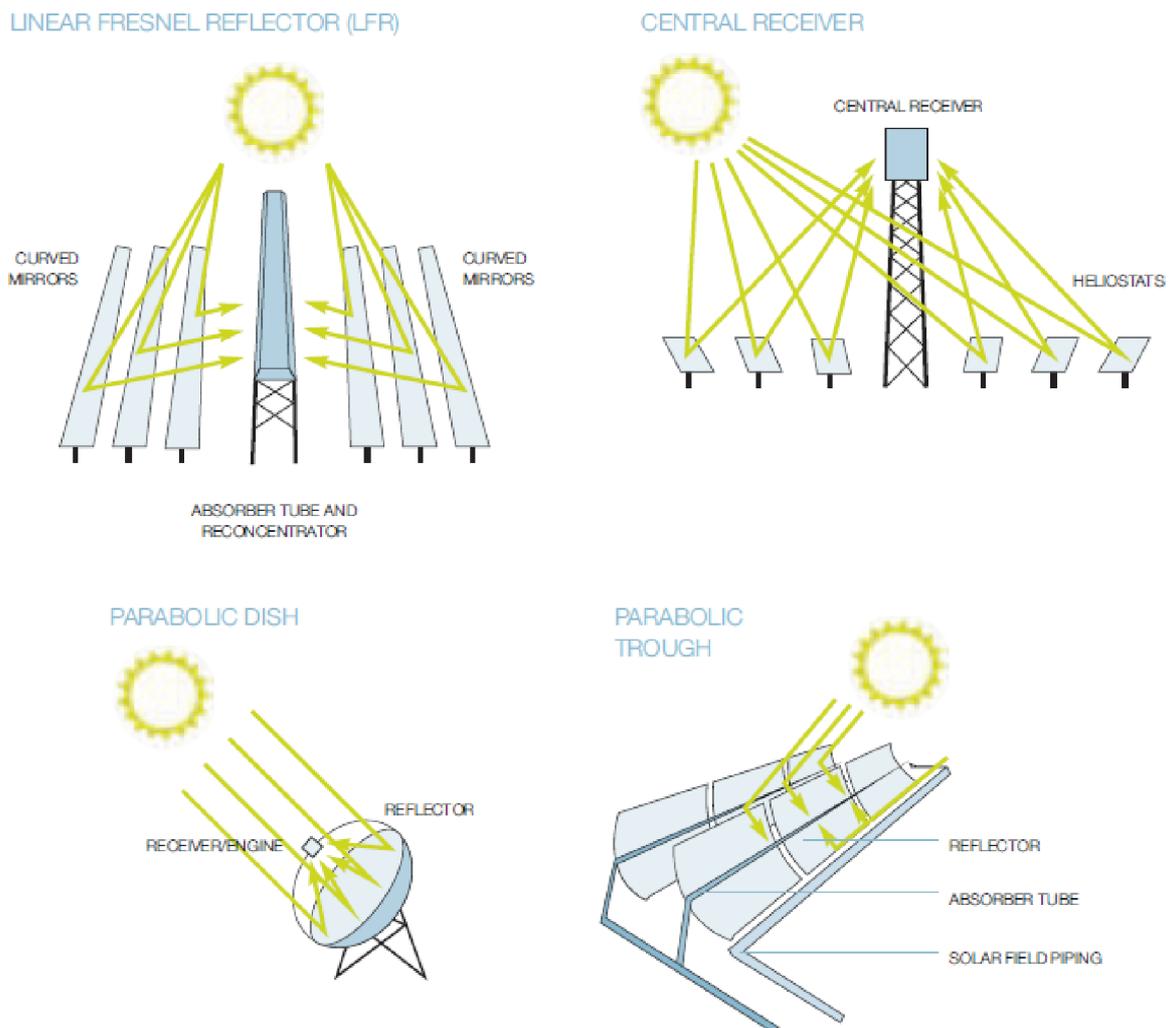


Figure 4 – types of Concentrating Solar Power plants [75]

### 1.2.2 Nuclear energy

One of the most controversial and cheapest energy sources is nuclear energy. **Nuclear fusion** is considered to be the most important energy source of the future; it is supposed to be powerful, clean and practically infinite. Scientists have been working on solution and presuming usage of nuclear fusion for energy purposes in 50 years. However, this

has been going on for 50 years now and they are still more or less 50 years from reaching the goal. The project all scientists are looking up to is called ITER (International Thermonuclear Experimental Reactor) and should be built in Cadarache, France. Unfortunately the recent economic recession has impacted negatively the budget of ITER project. United States are also working on laser ignition of nuclear fusion at National Ignition Facility in Livermore, California; experiments are on the run [4].

The commonly used nuclear reaction is **nuclear fission** with its more than 50 years long history in power generation. Ecological activists often bring up issues of nuclear waste and safety, especially after accidents in Chernobyl, Three Miles Island and most recently Fukushima. The fact is, there is the technology for nuclear fuel reproduction and governments in cooperation with companies have been working on technologies and projects for definitive storage of nuclear waste. As the potential damage caused by accident of nuclear power plant is huge, safety policies are very strict and safety systems multiplied. In context of the most devastating accident in Chernobyl is very important and commonly ignored existence of various types of nuclear fusion reactor. BWGRs (boiling light-water-cooled, graphite-moderated reactors) used in Chernobyl were used only in former Soviet Union and their further development was scrapped after the accident. The majority of currently operating and planned nuclear reactors is represented by PWRs (pressurized light-water-moderated and cooled reactors), which are distinguished by capability of self-regulation and increased safety. Therefore there is no wonder, the nuclear power plants are the safest power plants in the world [5]. Even some of the ecologists including co-founder of Green Peace organization Dr. Patrick Moore [6] realize, that **nuclear energy will play key role in lowering carbon dioxide emissions** as a base-load energy source.

Development until the Fukushima accident confirmed this statement – in 2010 trading on the uranium year-to-date spot market reached record volume almost 19 000 tons, beating two decades old record [7]. According to Table 1 - Nuclear power reactors under construction (as of 1 January 2010) [8], there was 56 units under construction with total power 52 GW and growth is expected in the following decade. Currently economically reachable uranium reserves should last more or less 100 years. Adding gaining from phosphates means extension to few hundred years. Reserves in sea water would last 80,000 years. The time will be extended with common usage of FBRs (fast breeder reactors) in on-going century.

The Fukushima accident in March 2011 raised yet another round of discussions about nuclear power and its safety. The determination of each country to use nuclear power has been questioned. Stress tests for reactors in operation were introduced and as a result of these tests further safety precautions have been recommended and implemented. No on-going construction was cancelled as most of the countries decided to analyse the accident properly and not to rush the decision. In context of nuclear power safety it is important to mention, that the only 2 victims of the accident at Fukushima Daichi were victims of a crane accident; no victims of radiation are reported nor expected. At the same time there is 20,000 reported victims of tsunami hit on 11<sup>th</sup> March 2011.

However, few European governments yielded immediate public opinion and decided to phase-out (Germany) or ban construction of new reactors (Italy, Spain, Switzerland) despite indisputable negative economic impact. The indisputability of negative impacts is demonstrated by Japan, where most of the nuclear reactors were temporarily shut-down until stress tests are finished. Nuclear power contributed to Japan's aggregate power generation by 30 %. Since the accident the country faces risk of extensive power shortages and utilities expect that consumers will face doubled electricity bills. Furthermore, the country recorded the worst trade balance ever, due to intensive import of fossil fuels required to compensate lack of nuclear power [9]. An extraordinary U-turn was committed by German government. In 2010 the coalition led by Angela Merkel postponed planned phase-out by a decade and approved possible lifetime extension in exchange for nuclear fuel tax. After this decision utilities invested hundreds of millions € to meet the lifetime extension criteria and paid another hundreds of millions in nuclear fuel taxes. These expenses became subjects of lawsuits and arbitrations against Germany after the phase-out decision made in May 2011 by the same coalition.

*Table 1 - Nuclear power reactors under construction (as of 1 January 2010) [8]*

<b>Country</b>	<b>Number of units</b>	<b>Power [MW]</b>
<b>Argentina</b>	1	692
<b>Bulgaria</b>	2	1906
<b>China</b>	20	19920
<b>Finland</b>	1	1600
<b>France</b>	1	1600
<b>India</b>	5	2708
<b>Iran</b>	1	915
<b>Japan</b>	1	1325
<b>Republic of Korea</b>	6	6520
<b>Pakistan</b>	1	300
<b>Russian Federation</b>	10	8007
<b>Slovakia</b>	2	782
<b>Taiwan, China</b>	2	2600
<b>Ukraine</b>	2	1900
<b>United States of America</b>	1	1165
<b>Total</b>	<b>56</b>	<b>51940</b>

### 1.2.3 Fossil fuels

As the fossil fuel extraction business is considered as very lucrative, there is no wonder, that involved companies are not particularly jubilant about current development. Additionally the fossil fuel burning power plants are commonly used and also the whole industry provides significant number of jobs. Therefore it has been worked on solution of carbon dioxide free fossil fuel burning power plants. The technology is generally called **Carbon Capture and Storage (CCS)**. The idea is to somehow catch carbon dioxide and store it or use in some other way. There are a few methods for carbon dioxide capture.

**Post-combustion** method based on “showering” flue gases with an amine solvent is principally similar to systems of nitrogen and sulphur capture from flue gases. However, this method has high energy requirements lowering efficiency by 20 % [10] (includes only scrubbing). A pilot-scale project is operated by RWE in Niederaussem, Germany.

Another method capturing carbon dioxide after combustion is called **oxyfuel combustion**. The scheme is very simple – instead of burning fuel in air, it is burned in almost pure oxygen. The nitrogen is separated before combustion, sulphur then using common procedures. Flue gases then contain water vapour, which can be easily separated by condensation, and almost pure carbon dioxide, which can be stored or used in other way. To reduce the flame temperatures, the flue gases are injected back to combustion chamber once they are cooled. Power plant using this technique produces absolutely no direct emissions at all, as they are all captured and stored. The 30 MW thermal oxyfuel pilot power plant was launched in 2008 by Vattenfall and Alstom in Schwarze Pumpe site in Germany [11].

The **pre-combustion** method relies on gasifying coal to synthetic gas – carbon monoxide and hydrogen. In water-gas shift reaction (also called syngas shift reaction) then carbon monoxide reacts with water vapour to form carbon dioxide and more hydrogen. The resulting gas consists of hydrogen and carbon dioxide, which is separated. The hydrogen can be used as fuel or in other way (petrochemical industry). However using hydrogen scheme for power generation is a little bit complicated, as there are no turbines, neither large-scale hydrogen infrastructure. An alternative route is gasifying coal to SNG (Substitute Natural Gas) and then use for common purposes including power generation. Definite advances of this approach are presence of large-scale natural gas infrastructure, no need to develop new types of turbines, possible operation 24/7 of the gasifier unit, possible lowering dependency on import of natural gas and total efficiency of electricity production just below 40 %. However, using the coal-SNG-CCS scheme leads to removing maximally 50 % of carbon [12]. To reach carbon-free electricity production additional post-combustion capturing at the gas power plant is needed.

Captured carbon dioxide is then transported usually by pipelines to the place of storage. There is also on-going research for re-use of carbon dioxide in different ways, typically transforming it to methanol or other hydrocarbons. In theory, there are few possibilities of carbon storage – geological, mineral and ocean storage. Geological storage

means injecting carbon dioxide back to oil or gas fields and other stable formations. Mineral storage is natural process creating stable carbonates from metal oxides. It can be fastened by changing reaction conditions – higher temperature and pressure. However, the energy demands of such industrial solution are still unacceptable. Ocean storage counts on dissolution and storage on the sea floor in great depths. The requirements for permanent carbon dioxide storage are not far from those for final repositories of nuclear waste – the storage have to be definite, in geologically stable location and can't put any demands on future generations. Potential leakage can be locally very dangerous and would make the investments in CCS useless. Nevertheless, reliability and industrial deployment within period of two decades is questionable.

Another way, how to make fossil fuels usage more ecological is employing natural gas-fired **Combined Cycle Power Plants** (CCPPs), which use Combined Cycle Gas Turbine (CCGT) and Heat Recovery Steam Generator (HRSG). Principle is simple – flue gases from gas turbine are used to produce steam in HRSG, which then drives conventional steam turbine. This scheme leads to overall efficiency 50 – 60 %. Study by Energy Information Administration [13] shows, that combustion of natural gas produces 40 % less CO<sub>2</sub> than coal, 75 % less CO and NO<sub>2</sub> and non-relevant volume of SO<sub>2</sub> and particulates. Additionally, the start-up time of combined cycle is only 30 minutes. Reaching full-load from “parking” at low load ( $\approx 20\%$ ) takes only 15 minutes. This makes CCPPs suitable compensating units in renewable energy based systems and a convenient replacement for old coal-fired plants – it is more environmentally friendly and provides better flexibility. In United States prices of natural gas dropped after shale gas production was deployed, while in Europe further pipes from Russia are built – half capacity of Nord Stream is available since autumn 2011, construction of South Stream began - and Nabucco pipeline delivering natural gas from Iraq, Azerbaijan and Turkmenistan is considered.

CCPPs are generally an excellent example of **increasing efficiency**. In general the process of increasing efficiency is a motive for technical development and has played key role in creating our society as we know it – shifting from gathering to farming, industrial revolution, information revolution, etc. Increasing efficiency in electric power domain is therefore important in order to lower emissions. There are several ways how to accomplish that - replacing turbines and appliances for newer ones with greater efficiency, increasing parameters (pressure, temperature) of steam loops, etc. One of the most effective is combined heat and electricity production, also known as **cogeneration**. Cogeneration uses residual heat of a steam or gas turbine to supply end users with heat. The efficiency depends on heat to electricity production ratio and could reach up to 80 %. Small cogeneration units have great potential for Smart Grids, while larger units provide greater efficiency and profitability. To operate larger units a central heating system needs to be built. These systems are widely and successfully used in former Eastern Bloc countries. However, the energy sources need to be renewed.

## 2 SUPER GRIDS CONCEPTION

### 2.1 Grids of the future

In general could be said, that mankind already have sufficient technology to produce enough electricity with significantly lower emissions. The question “Where is the problem?” comes out. Well, the problem, which many ecological activists don’t see, is how to efficiently transport produced electricity to the place of consumption and how to cover the changing demand of electricity. Electrical power network is a system where **balance is necessary** for its functionality – production equals consumption plus losses. Over- or underproduction leads to changing grid’s parameters and potentially can end up as a blackout, which of course have negative effects on economy and day-to-day life. So far distributors have been able to successfully predict and cover demand with fully controlled sources. However current hierarchical grids are not sufficient and sophisticated enough to face challenges of the future – to cover growing demand and to successfully integrate renewable energy sources. To solve this issue development and research might focus on two approaches - distributed Smart Grid and massive Super Grid. Before a closer look at these technologies is brought, it is important to point out, that these approaches are not necessarily contradictory; they can and in the future probably will successfully co-exist and co-operate.

#### 2.1.1 Smart Grid

Smart Grids are decentralized grids using two-way digital communication between consumer, nodes and supplier providing real-time information about production, demand and energy flow. Based on this information the system can automatically control and regulate itself and connected electrical units and appliances.

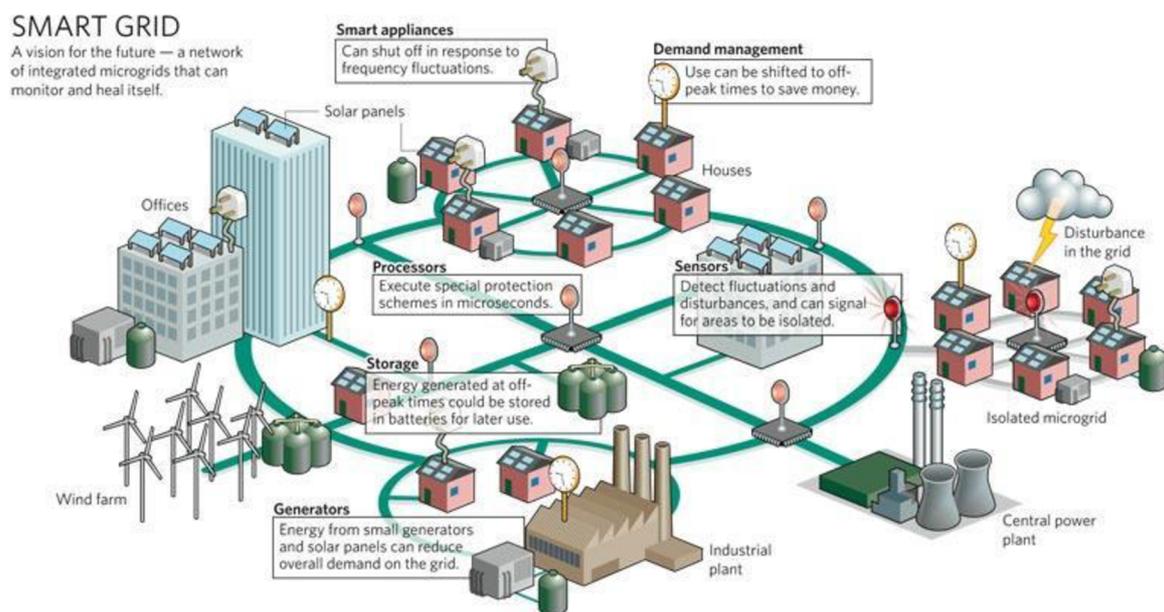


Figure 5 – Smart Grid concept [77]

From systemic point of view electrical power network is a system. This system is hierarchically dividable to subsystems – regions, cities, districts, streets or even houses. The aim of Smart Grid is to stabilize power supply of particular subsystems from external sources using active control of elements. In other words the goal is to smooth the curve of demand of external power, lower the dispersion of extremes, increase flexibility and improve prediction ability. If these principles and goals are applied to subsystems from the lowest level (i.e. houses) the control of the higher subsystem would be easier. As a consequence the aggregate electricity demand curve would be smoother, as well as its prediction ability and flexibility of the whole system would be significantly improved. Therefore more electricity could be produced in large primary and secondary electricity sources, which offer greater efficiency and profit ratio.

From perspective of energy sources typology the goal of Smart Grid could be described as integration of renewable and other local energy sources on local level. In real life, the grid should for example turn on end user's washer, boiler or charge electric car when consumption in the area is low or wind is optimal to connect local wind power plant to the grid. The Smart Grid concept includes Smart Metering (sometimes also called Advanced Metering) technology, therefore the whole system becomes more transparent and the consumer is able to have real-time information about consumption and costs. The system also helps to detect unregistered leads and cut off the unpaid ones without any field operation as well as restore connection after accident etc. This way distributors can not only safely integrate renewable and other local energy sources, but also increase efficiency, reliability and lower costs. Also requirements are reasonable - Smart Grids can use current AC (Alternating Current) infrastructure adding another layer – two way communication.

Both all the main technologies and infrastructure have been developed, what is missing then? According to Mark McGranaghan [14] *“The biggest gap is the lack of inexpensive, standardized, and ubiquitous communications that deliver bandwidth, extreme reliability, and security for both control and management applications as well as basic information management and sharing applications. This broadband communications infrastructure does not need to be one technology, but it needs to extend all the way from central control systems to end-user devices.”* Also privacy issues are brought into the discussion. Nevertheless, many companies have come up with their Smart Grid pilot projects. World's biggest Smart Metering project launched by Italian Enel [15], introduced in 2005, currently covers 32 million customers and will be deployed also in other regions. Central Europe's biggest electricity producer ČEZ came up with “Smart Region” project in Vrchlabí, Czech Republic [16]. This project does not include only Smart Metering, but also includes automation and monitoring components for distribution grid, infrastructure for electric cars, electric cars itself and safe integration of local energy sources, especially the renewable ones. Full operation is expected by 2015. Very interesting approach was taken by Exelon Corporation's subsidiary ComEd in Chicago [17] – their project equips 8,000 homes with different types of Smart Meters enabling different levels of user monitoring and control and observes which one provides the best results. The project can potentially grow to 130,000

homes and will include solar systems for 100 homes. Recently launched and fully operating Toyota's Smart Village in Japan [18] includes 6 houses and 8 Toyota Prius plug-in hybrid cars; for power generation are used exclusively renewable energy sources.

### 2.1.2 Super Grid

Super Grids are wide area high-voltage networks for transporting huge amount of electricity across long distances. The idea is to use Super Grid as an overlay layer over present AC (alternating current) grid to transport power from huge distant renewable sources to place of consumption all over the continents and solve problems with local electricity over- and underproduction. Whereas conventional grids were designed for transmission of hundreds of megawatts across at most hundreds of kilometres, Super Grids should be capable of transmitting gigawatts across few thousands kilometres.

The concept is based on few facts and ideas. Firstly, it is both economically and environmentally correct idea of using wide in other ways non-utilizable areas, such as deserts, tundra or seas, for electricity production. According to Dr. Gerhard Knies [19], Chairman of the Supervisory Board of the DESERTEC Foundation, *"Within 6 hours deserts receive more energy than humankind consumes in a year."* However, it is not only about solar energy. These distant uninhabited areas can be used for building wind, hydro and nuclear power plants as well. Huge energy losses cause that such approach is uncompetitive and therefore impossible to implement, if conventional grids are used. The simplified idea is that the wind is always blowing somewhere or the sun is shining somewhere. In other words, there is always a possibility to generate electricity somewhere and transmit it using Super Grid to the place of demand with reasonable energy losses; and vice versa – overproduction is always consumed somewhere. From systemic point of view Super Grid is a robust system which gains its strength and stability with growing number of elements and connections. It is not convenient to divide this system to subsystems, because it relies more on number of sources and places of consumption and complex functionality. Analogical example of such system in real world is cloud computing in large datacentres, where the efficiency grows with growing number of computing units and customers.

Both typological and geographical diversification of energy sources is absolutely vital for Super Grid in order to secure required electricity supply. If the need of diversification is ignored, a Super Grid alone is not a recipe to fight black-outs. Super Grid on a relatively small area would suffer from small amount of energy sources and places of consumption. The idea that the electricity can be always produced or consummated "somewhere" would not be applicable anymore, because on small area the curve of demand or available power of energy sources of the same type is likely similar. A Super Grid built on basis of one or two types of energy sources also wouldn't fulfil its function. An extreme example of such arrangement would be a Super Grid based on solar power plants – without energy storage, no or very low power would be produced during night, even when spread across the whole continent. Super Grids need various energy sources – renewables with power limited by weather conditions,

hydro power plants, well-controllable fossil fuel fired plants and base-load nuclear power plants.

A Super Grid provides more abilities than just profitable electricity generation at distant power plants. Increased transmission inter-regional and -national capacity opens possibility to integrate and liberalize electricity markets and increase trading volume. Higher trading volume would lead to reducing usage of unprofitable energy sources, Pareto efficiency of the system and drop of electricity prices. Benefits of such arrangement are commercially proven by few examples of established market coupling in Europe (Czech Republic – Slovakia, Netherlands – Norway, Germany – Denmark, etc.). Extensive change of legislation would be required – not only in market area, but also in area of subsidy of renewable sources. In Europe the subsidy policies differ by country, which would create distorted market conditions in an integrated electricity market. As Alan Svoboda, Chief Sales Officer at ČEZ, argues [20], emission allowances trading should replace gigantic subsidy as it is fair across industries, energy sources and countries. The European Union Emission Trading System (EU ETS) has so far failed its goal due to excess of available emission allowances and economic recession, which led to game-changing drop of prices.

Super Grids as any other massive concepts face a series of problems – technical, political and most important economical. As well as for Smart Grids, all the major technologies for Super Grids have been developed. The problem here is the size of the project. So-called “electricity highways” or “electricity backbone” has to be built. This backbone should consist of number of high-voltage AC (Alternating Current) and DC (Direct Current) links with great transmission capacity, connecting different parts of a continent, including large consumption or generation centres. Consumption centres already exist in form of densely populated and heavy industrialized agglomerations. The generation centres, however, need to be built as well covering wide range of energy sources, as mentioned above. It will require cooperation of many nations and companies to implement this concept in energy transmission system due to enormous investment costs, required legislation changes and convoluted permission processes.

### **2.1.3 SuperSmart Grid**

Until 2007 it has been silently assumed, that Super Grids and Smart Grids are mutually exclusive concepts. However, discussion led by Antonella Battaglini and colleagues [21] at European Climate Forum showed that this is not true. These concepts actually can work side by side profiting from capabilities of both concepts creating a synergic effect. It turned out, that massive Super Grid requires the same system approach as Smart Grid – distributed power generation, just on much larger area. Therefore it can use some of the control technologies and easily co-operate with Smart Grids. Local Smart Grids would become elements of a superior Super Grid with stable and predictable electricity demand or supply. This would result in creating a next-gen grid capable of integrating everything from single wind turbines to huge solar parks, covering local and regional shortage and using non-utilizable areas for power generation purposes.

The idea of SuperSmart Grid as presented by Battaglini and colleagues counts exclusively on massive use of renewable sources. They argue by bad commercial success of Carbon Capture and Storage systems and incapability of adequate growth of nuclear industry. However, renewable energy industry is not capable of such growth to fully replace fossil fuels in acceptable time horizon either; not to mention much greater costs of construction causing inconvenient increase of electricity prices by hundreds of per cents. Additionally, as mentioned in chapter 1.2.1 “Renewable energy sources”, massive use of wind and solar energy is impossible with current conventional grids in order to secure stability of the grid. Therefore it is logical to come to an assumption, that conventional power sources will be at least temporarily a vital part of the future grid and should be included in concepts like SuperSmart to keep them realistic.

## 2.2 Technology overview

Two main technologies are considered for Super Grid, HVDC (High-Voltage Direct Current) and HVAC (High-Voltage Alternating Current). Absence of ubiquitous standardization of voltage ranges causes confusion and usage of few abbreviations in context of high-voltage bulk-power transmission. In general HVDC and HVAC cover range over 100 kV, corresponding normalised levels in Czech Republic using Czech abbreviations are “vvn”, “zvn” and “uvn”. Terms UHVDC (Ultra High-Voltage Direct Current) and UHVAC (Ultra High-Voltage Alternating Current) are often used for systems using voltage above 800 kV. Abbreviations EHVDC (Extra High-Voltage Direct Current) and EHVAC (Extra High-Voltage Alternating Current) are used rarely, typically mentioning systems with voltage above 325 kV.

For purpose of this thesis, only terms **HVDC** and **HVAC** will be used.

### 2.2.1 HVDC

Majority of planned projects counts on HVDC technology. This is not a completely new technology, as it has been successfully used over past decades, especially for undersea electricity transmission. In fact, at the very beginning of electricity transmission mainly DC systems were used, typically as a direct connection between hydropower plant and factory. Later, when electric power grid was built and different voltage levels were required, AC systems were easier to implement.

Today HVDC links are used as a part of AC grids. Usually HVDC links connect two points. The connection points are called terminals. Systems where more than two terminals are used (for example connection between Corsica, Sardinia and mainland Italy) are called multi-terminal systems. The general principle is that at one terminal alternating current is rectified (conversion AC  $\rightarrow$  DC) and at the other terminal is the direct current again amplified (conversion DC  $\rightarrow$  AC).

At Figure 6 can be seen simplified block schematics of a terminal, specifically converter station. The main parts are transformer and converter. Since direct current cannot be transformed, the desired voltage has to be acquired at AC side. Converters are capable of

either rectifying or amplifying. Modern converters are typically formed by valves of IGBTs (Insulated-Gate Bipolar Transistors) or thyristors. Since these semiconductor devices cannot handle voltage of hundreds kV, they are connected in series. To guarantee equal voltage distribution among devices a very precise control is required. This is the reason why a dedicated control system is used. The converter produces higher harmonics on the AC side and consumes reactive power. Therefore AC filters and shunt capacitor units are installed. The size and power of this filtering equipment and compensation units differs from technology used in converter. The output DC voltage is not perfectly direct, therefore smoothing reactors and DC filters are present on DC side as well, especially in case overhead HVDC lines are used.

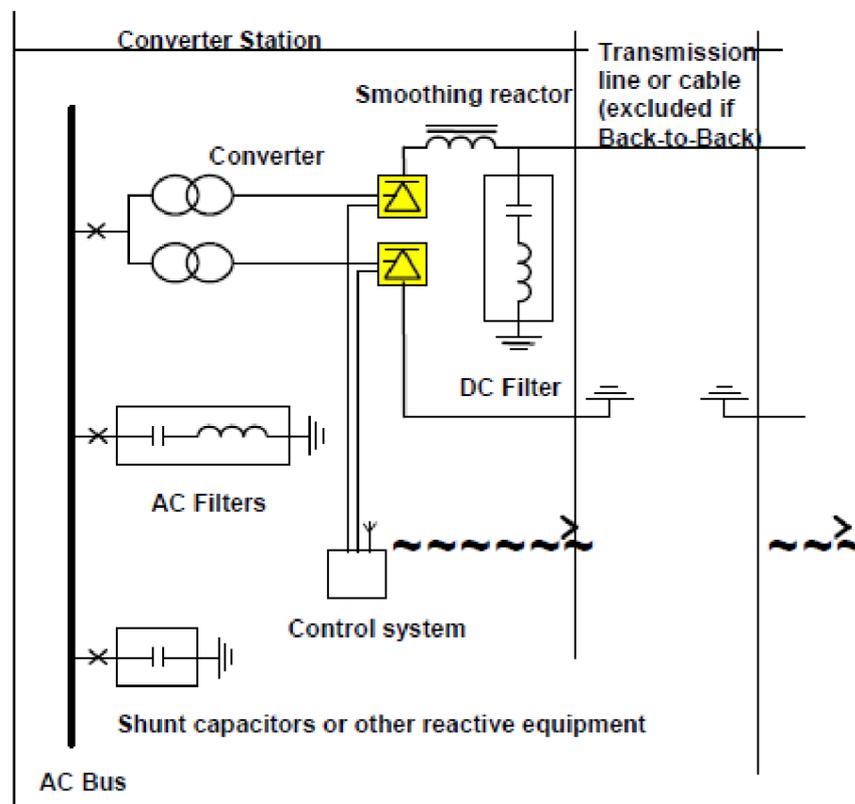


Figure 6 – Simplified block schematics of a converter station (terminal) [28]

### 2.2.1.1 Pros and cons of DC usage for bulk-power transmission purpose

The main reason why DC systems are again brought under consideration are **lower energy losses**. Both overhead power lines and underground or undersea cables (described in chapter 2.2.1.4) can be characterised by following attributes – inductive reactance ( $X$ ), capacitive susceptance ( $B$ ) longitudinal impedance ( $Z$ ) and transversal admittance ( $Y$ ).

$$X = 2\pi \cdot f \cdot L \quad (1.1)$$

$$B = 2\pi \cdot f \cdot C \quad (1.2)$$

$$Z = R + jX \quad (1.3)$$

$$Y = G + jB \quad (1.4)$$

It is obvious from equations (1.1) and (1.2), that these parameters depend on frequency. Despite parameters as presented are mainly used in model-based calculation of 3-phase AC lines (Telegraph equations), or in differential form for calculation of 3-phase AC lines with equally distributed parameters, it is clear, that lack of alternating component leads to much lower losses if lines of same length and parameters are considered. With increasing length, the impedance, admittance and losses are growing, as well as angle. Therefore for HVAC transmission reactive power compensation units are required. Yet, after reaching certain length, transmission capability of an AC lines drops and eventually becomes not reliable, as shown at Figure 7 – Degrading transmission capability of 1000 kV AC line with max. compensation 70 % and angle 30°. In reality, transfer of 1 GW across 1000 km using HVDC technology is done with losses approximately 3 % + 0.6 % per terminal.

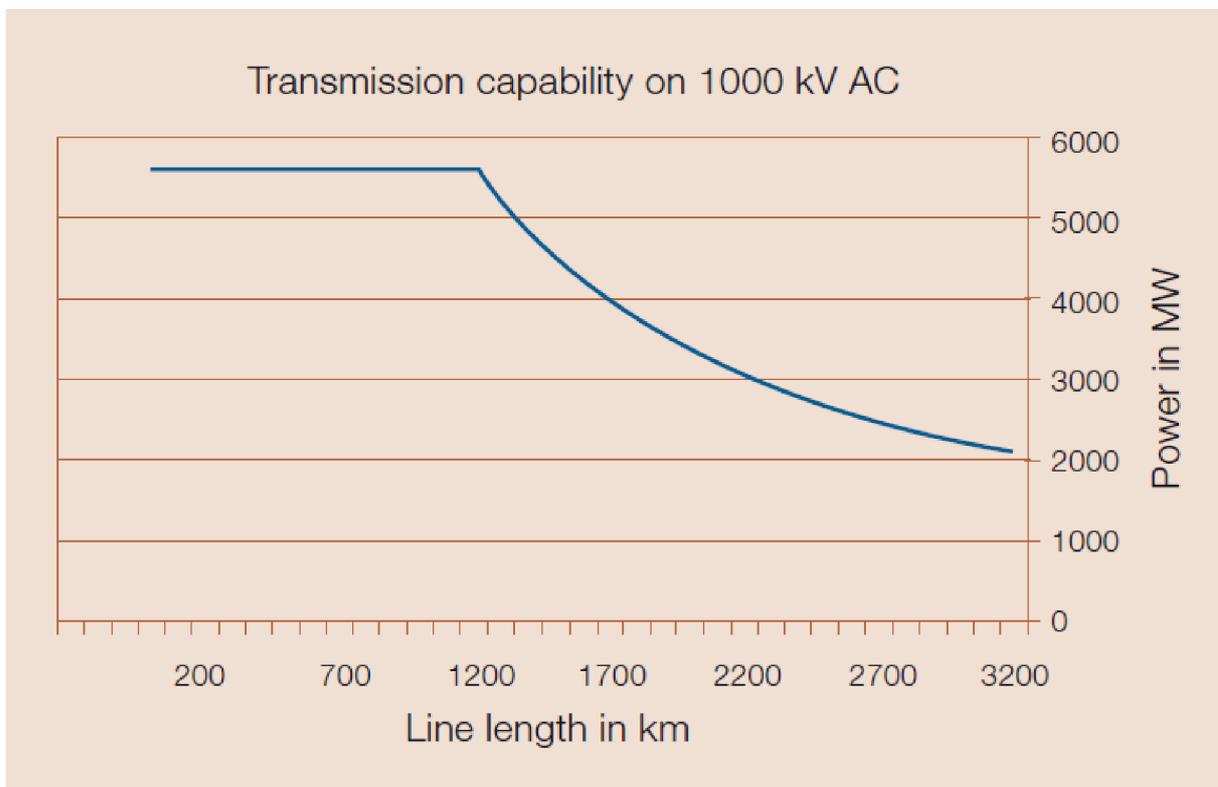


Figure 7 – Degrading transmission capability of 1000 kV AC line with max. compensation 70 % and angle 30° [22]

The effect of reactive losses is intensified, if cables are used for transmission, typically submarine cables. Therefore usage of HVDC for undersea bulk-power transmission is comparing to overhead lines more frequent.

The **potential of particular components is better utilized** in case of DC technology. While designing components, two main parameters are considered – voltage and current. Whereas for effects of current both in DC and AC systems the RMS (root mean square) value (a.k.a. effective value) is considered, for voltage dimensioning peak values are used. As it is

clear from equation (1.5) for sine wave peak to peak value, the peak to peak voltage value in AC system is approximately 1.41 times greater comparing to DC system.

$$U_{PP} = U_{RMS} \cdot \sqrt{2} \quad (1.5)$$

Because single HVDC line is capable to transmit much more power than single HVAC line, **smaller corridor is required** and less transmission towers has to be built, if rated power exceeds a single AC line capacity. As Gunnar Asplund from ABB argues [22], “*transmission of 12,000 MW can be achieved with two lines using 800 kV HVDC. Transmitting the same power with 800 kV AC would require eight lines.*” Additionally, both HVDC lines can be operated on a single set of towers. The difference is remarkable and provides considerable reduction of costs and environmental impacts.

In general, the decision to use HVDC for bulk-power transmission is usually driven by an **economical evaluation** and financial analysis. DC systems do provide much lower losses of energy and therefore also reduce cost of transmission, particularly variable cost. The difference is growing with distance and transmitted power in favour of HVDC. Additionally, in case of power requirements in range of units of GW, costs of HVDC lines are lower because of less lines are needed. However, HVDC systems require installation of costly terminals, which represent fixed investments. The suitability of HVDC link therefore highly depends on length and power. In general, for shorter links or links with less power AC systems are more economically justifiable, while for longer distances and higher power HVDC systems are more suitable, as the break-even point analysis at Figure 8 shows. The break-even distances are over 800 km in case of 3500 MW and over 600 km for 10 500 MW link.

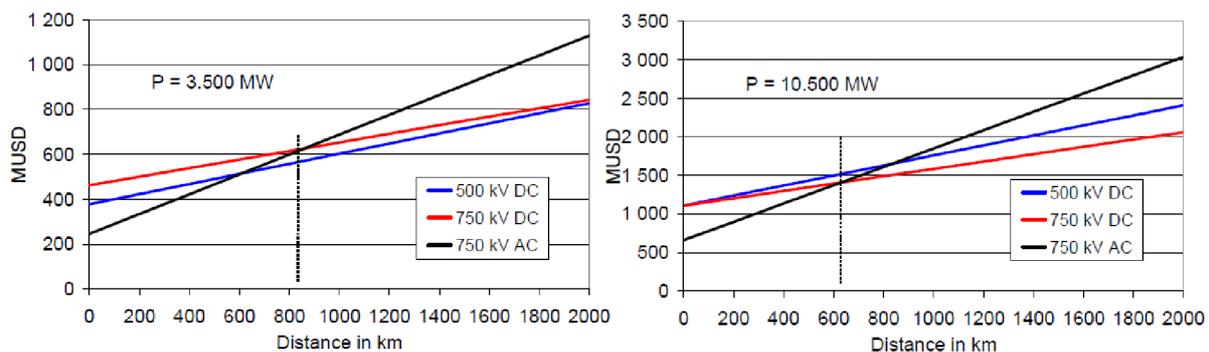


Figure 8 – Total cost for transmission lines and station for 3500 MW and 10 500 MW with break-even points [79]

For underground and submarine cables the break-even distances are much lower even at much lower power levels. An excellent comparison of AC and DC transmission across 100 km using the same cables was presented by Karel Malý and František Němeček [23]. For comparison a 150 mm<sup>2</sup> single core lead-covered cable with impregnated paper insulation designed for 50 kV AC transmission was used. The 3-phase transmission capacity was up to 20 MW (angle = 0°) and for length of 100 km the losses were 3.2 MW, which is 20 % of transmitted power. The same cable could be also operated at 200 kV DC, where using bipolar

configuration the transmission capacity reached 110 MW with losses 2.9 MW  $\approx$  2.6 % of transmitted power. Even though the comparison was made some 50 years ago and the technology of cables has improved, the difference is still remarkable. Therefore in these applications HVDC systems are used almost exclusively.

Another capability of an HVDC link is to **interconnect two or more asynchronous AC grids**, even if they use different frequencies.

### 2.2.1.2 Configurations

Two configurations are typical for HVDC bulk-power transmission – monopolar and bipolar. Schemes are shown at Figure 9.

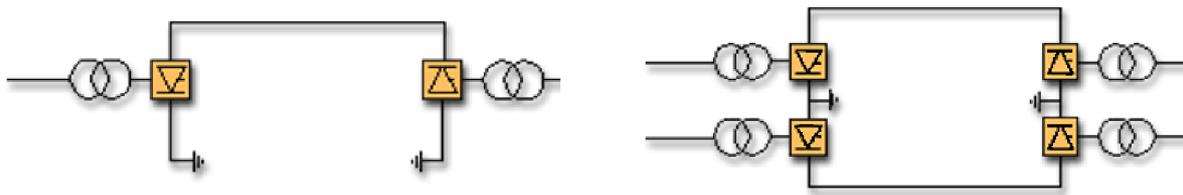


Figure 9 – Monopolar (left) and bipolar (right) configuration [25]

**Monopolar** systems use only one conductor for power transmission, which is high above ground potential. The other poles of converters are grounded and therefore the current flows through earth. This arrangement, known as single wire with earth return, leads to unpropitious environmental effects such as corrosion and change of water chemistry. Therefore a conductor is added. This arrangement is called monopole with metallic return. The advantage is that the metallic return conductor doesn't have to be insulated for full voltage. However, grounding of the metallic return or converters is required to provide DC voltage reference. Monopolar systems are the least complicated and expensive. The simplest design counts only with two converters and one conductor. Therefore they are very popular, especially for lower power levels.

**Bipolar** systems use both halves of alternating component, therefore two conductors with potential high above ground potential, but of opposite polarity, are used. Both conductors have to be insulated and protected for full voltage. On the other hand, the transmission capacity is double and the reliability higher. In case a fault occurs at one of the lines, the other one can be operated with earth return and the total capacity of the link drops to a little bit less than a half. Under normal operation the return current flow is incomparably lower to monopolar solution. To prevent negative environmental effects earth-current conductor can be installed as well. There is also a possibility to install bypasses to converters, thus enabling operation at 50 % capacity in case of converter outage (for example failure or maintenance) using the unloaded conductor for metallic return. Bipolar setting is typical for majority of high-capacity HVDC systems, especially overhead lines.

Need to connect two or more converters per pole into **series** arises at higher voltages, typically above  $\pm 500$  kV. Converters connected into series increase availability and reliability by providing partial capacity in case of single converter failure or reduced insulation

capability of a conductor. For example, if two converters are used per pole and terminal, and one of them is shut-down, the system's capacity would be 75 % of total designed capacity, instead of 50 % if one pole would be shut down or 0 % in case of failure of monopolar system.

There are also applications, where two asynchronous grids meet at certain power station or small area and only very short line is required, typically state boundaries in populated areas. Such an arrangement is called **back-to-back** HVDC system. Back-to-back systems are also used in places, where appliances require high-quality electricity of certain parameters [24] [25] [26].

### 2.2.1.3 Converters

Converters are the essential components of a HVDC system as a part of electrical grid, as they are the devices responsible for AC to DC and vice versa conversion. Today typically 12-pulse converters are used for each pole (in case of bipolar system), thus providing two independent DC circuits of half capacity. 12-pulse converters are formed by two 6-pulse bridge converters shifted by 30°. The phase-shift is created by the transformer with two secondary windings, one delta-connected and one star-connected. Each converter consists of valves of semiconductor devices – IGBTs or thyristors in order to operate at required high-voltage level.

Converters can be divided into two groups – line-commutated CSCs (Current Source Converters) and self-commutated VSCs (Voltage Source Converters) [27]. While line-commutated converters typically use thyristor valves and are operated at AC grid's frequency (50 or 60 Hz), self-commutated converters typically use IGBTs and much higher frequency [28].

**Line-commutated Current Source Converters** are historically older technology used since the very beginning of commercial HVDC technology usage. Mercury arc valves had been replaced for thyristor valves and became part of history in recent years. At this time, thyristors up to 8500 V / 2000 A (or 6500 V / 4250 A) are available [29]. Thyristor-based converters use natural commutation and are capable of both-way overvoltage blocking. Line-commutated converters require connection to the synchronous AC grid for their operation, and quite a strong one, as the commutation process requiring current lagging voltage needs stable delivery of reactive power. The reactive power is also provided by AC filters and shunt capacitors, yet some links are too weak. Therefore a **CCCs** (Capacitor-Commutated Converters) were introduced in late 1990s. CCCs also use thyristor valves. However, there are added serial-connected capacitor units at AC side of convertor, thus reducing the need of reactive power. This technology is proven, but not widely spread.

Systems based on Current Source Converters are suitable for bulk power transmission across long distances using ultra high voltage levels and are widely used in conventional HVDC systems. These systems are typically bigger, more robust, provide better profitability, but as it was already mentioned, require compensating unit.

The development of **self-commutated Voltage Source Converters** rapidly accelerated in new millennium. Valves of IGBTs are typically used; usage of GTOs (Gate Turn-Off Thyristors) or IGCTs (Integrated Gate-Commutated Thyristors) is also possible. Current state-of-the-art IGBTs are 6500 V / 750 A (or 4500 V / 1200 A) [30]. The main advantage of these devices is the possibility not only to turn-on but also to turn-off using control signal. The main principle of current conversion is PWM (Pulse Width Modulation) using commutation frequency up to 2000 Hz. Such high frequency significantly improves reaction time and control abilities of the converter. The possibility to control voltage amplitude and angle regardless current means, that VSC system is capable of both production and consumption of reactive power depending on needs of the synchronous grid. Additionally this ability is available at each terminal of a VSC HVDC link, hence granting added value and becoming an important tool for increasing power system stability. The operation load range is 0 – 100 %; a start from the black is possible. Thanks to excellent controllability it is also an ideal technology for a multi-terminal HVDC system. Lower costs, increased connection compatibility and modularity of VSC technology increased feasibility of HVDC links starting at 200 MW and 60 km. In combination with start from black ability and positive impacts on AC grid's stability, the usage for large-scale renewable sources, especially off-shore wind parks, is more than convenient. Smaller dimensions of converter stations also made possible installation at off-shore oil and gas platforms. IGBTs are capable only of one-way voltage blocking. Also the losses are higher, due to high modulation and switching frequency. The construction time of VSC station is estimated to be 1 year, three times shorter than for thyristor-based CSC. No shunt capacitors are required and the AC filters can be comparably smaller, due to capability to control reactive power flows and lack of harmonics. Requirements are put on converter reactor, which is connected closely to the converter valves, as it has to filter high-frequency pulses of PWM.

Systems based on Voltage source converters technology have been given commercial name HVDC Light (ABB), respectively HVDC PLUS (Siemens). HVDC Light systems offer modular solution – 9 power levels of converters (3 voltage levels  $\times$  3 current levels) and standardized both underground and submarine cables covering range 200 MW – 1200 MW. Usage of HVDC Light is convenient for smaller application, in correspondence to presented power range, especially for cables usage. Further development and deployment of this technology is expected. Current limitations are given by voltage and current limitations of IGBTs and relatively high switching losses. Focus on reduction of switching losses leads to innovations in converters topology and control systems, such as MMC (Modular Multilevel Converter) using cascaded connection logic (Figure 10) [31].

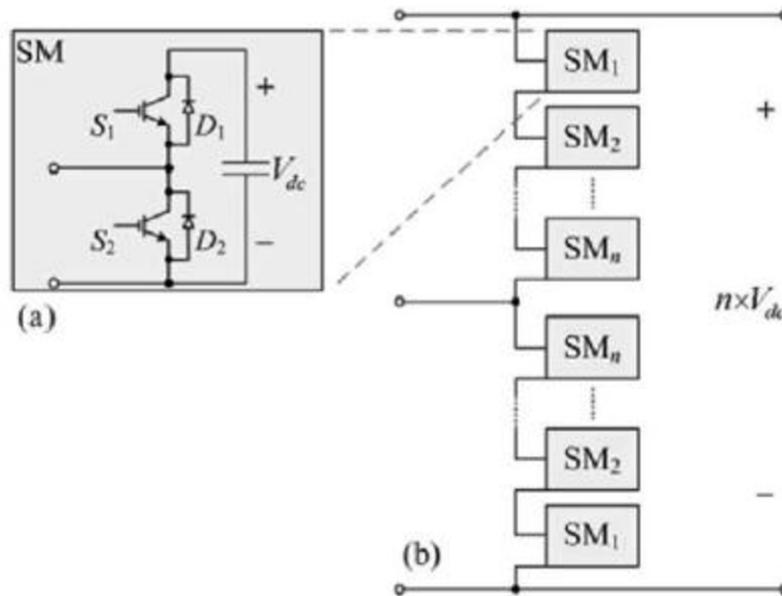


Figure 10 – Modular Multilevel Converter topology [31]

#### 2.2.1.4 Cables, lines

There are two ways how to connect two terminals – using **overhead lines** or using **cables**. The usage of cables for transmission across larger water bodies is obvious. Cables for this application are called submarine cables, even if they are laid across lake or river. There are, however, cases, where cables are used at land and called underground cables.

**Overhead lines** (OH lines) enable usage of ultra-high voltages. At the time  $\pm 800$  kV bipolar HVDC systems are commercially available and provide the lowest losses, reasonable costs and thus the best profitability for long-distance bulk-power transmission. The Xianjiaba – Shanghai link in China, one of the longest links and most powerful HVDC system in the world, in operation since July 2010, transfers up to 7200 MW across 2000 km with losses of only 7 % [32]. The width of a corridor for each HVDC line is approximately 50 m.

Such high voltage leads to very tall transmission towers, up to 90 m. The large dimensions of towers combined with enormous potential of conductors increase probability of a lightning strike. Due to stable polarity of conductors, also the probability is not equally distributed as it is in case of AC transmission. New methods of lightning strike risk analysis and design of towers and shield wiring have to be adopted. The calculations using fractal method include some random factors and provide more consistent results with real data, in comparison with EGM (Electro-Geometric Method), as presented by J. L. He and R. Zeng [33]. According to their calculation, the conductor of positive pole has a 4 times greater probability of a lightning strike comparing to conductor of negative pole.

The development in overhead lines and electricity towers fields is not rapid. The growing extremization of weather leads to more frequent stresses of transmission towers and as a consequence occasional collapses. Therefore efforts to improve towers' design towards

greater stability and reliability have been made. According to Milan Bartoš [34], specialist at SAG Elektrovod, the conventional lattice steel design has reached its limits, while tubular design proved increased resilience in both testing facilities and unfavourable conditions in various northern countries. This change of design could become leading innovation of the industry in upcoming decades.

Yet the demand of **underground cables** is likely to grow. Comparing to overhead lines, cables provide few advantages:

- lower maintenance costs (frosting, regular corridor-cleaning);
- better endurance to unfavourable conditions – storms, wind, frost, tree-falling;
- lower environmental impact (no visible towers build);
- possibility of multiple usage of right of way (more lines, optical cables, etc.);
- possibility to use the soil for other purposes at the same time;
- no audible noise;
- significantly reduced electrical field emissions;
- smaller corridor;
- easier to get right of way.

Growing electricity demand in heavily populated areas is causing current transmission capacities insufficient. At the same time it is impossible in democratic countries to build massive overhead lines in city centres or populated areas in general. The issue of getting right of way for linear constructions in general has a growing importance and together with permission processes for other components of energy system often are causes of delay or scrubbing of a project. For example in Germany, 800 km of overhead lines was planned to be built during past decade. In reality, only 10 % of total planned length was built, thus putting stress on the grid. Therefore underground cables providing advantages mentioned above become a competitive alternative, despite higher losses and investment costs. The total costs of 1GW bipole HVDC underground cables are estimated to €1 million - €2.5 million per km, approximately 3 times higher comparing to an overhead line [35].

The environmental impacts of HVDC cables are reasonable. For underground cables, laying in tranches is used. Cables are laid in sand 1.5 m below surface. The width of a trench for one bipole is less than 1 m. If more bipoles is installed, only the width increases. There is a requirement, to clear deep-rooted trees in 2 m strip around the corridor. While for 5 GW HVDC overhead line would require right of way 50 m wide (using  $\pm 800$  kV), for cables usage only width of 12 – 15 m depending on cable and converter technology would be needed. The electromagnetic field pollution is negligible. Heating of the ground is not thoroughly measured, but is estimated not to exceed 1 °C at the surface, thus not causing any damage to the growth of plants.

Two main technologies are used for cable insulation – MIND and XLPE. MIND stands for mass-impregnated, non-draining, paper insulated cable [36]. The conducting core is surrounded with semi-conducting carbon paper. Main insulating layer is formed by thin paper layers which are first dried-off and then impregnated with insulation oil. The whole cable is

hermetically sealed; mechanical endurance is given by steel tape and double-layered steel wire armour. This technology is proven by more than 40 years of commercial usage. It is also widely available. However with development of converters usage of MIND cables is on decline in favour of polymeric XLPE cables, which has been used for AC transmission since 1960s [26]. The technology remained in the basis the same, the polymer insulation has been improved over the years. Comparing to MIND cables, XLPE cables provide better manipulation properties. According to Europacable, association of European manufacturers of wires and cables, the capacity of XLPE cables production in Europe reached in 2011 3500 km and is likely to grow further [37].

Lower energy losses of DC cables comparing to AC cables were mentioned earlier in chapter 2.2.1.1 “Pros and cons of DC usage for bulk-power transmission purpose”. However, there is more to comparison of XLPE AC and DC cables. To avoid magnetic losses in cables, AC cables require non-magnetic armour, for example stainless steel wires, copper or aluminium alloy. DC cables do not require such armour and galvanized steel can be used as well. To transfer same amount of power, AC submarine link requires 3 conductors, additionally with larger cross-section, while DC link utilizes only 2 conductors with smaller cross-section. This leads to reducing weight by 60 – 70 % and thus reduces costs and difficulties with transportation and laying.

The cables used on land and in water bodies differ, as shown at Figure 11, but fundamentally the technology is the same. ABB’s HVDC Light technology offers submarine cables typically with copper conductor of cross-section 95 mm<sup>2</sup> – 2400 mm<sup>2</sup> and steel wire

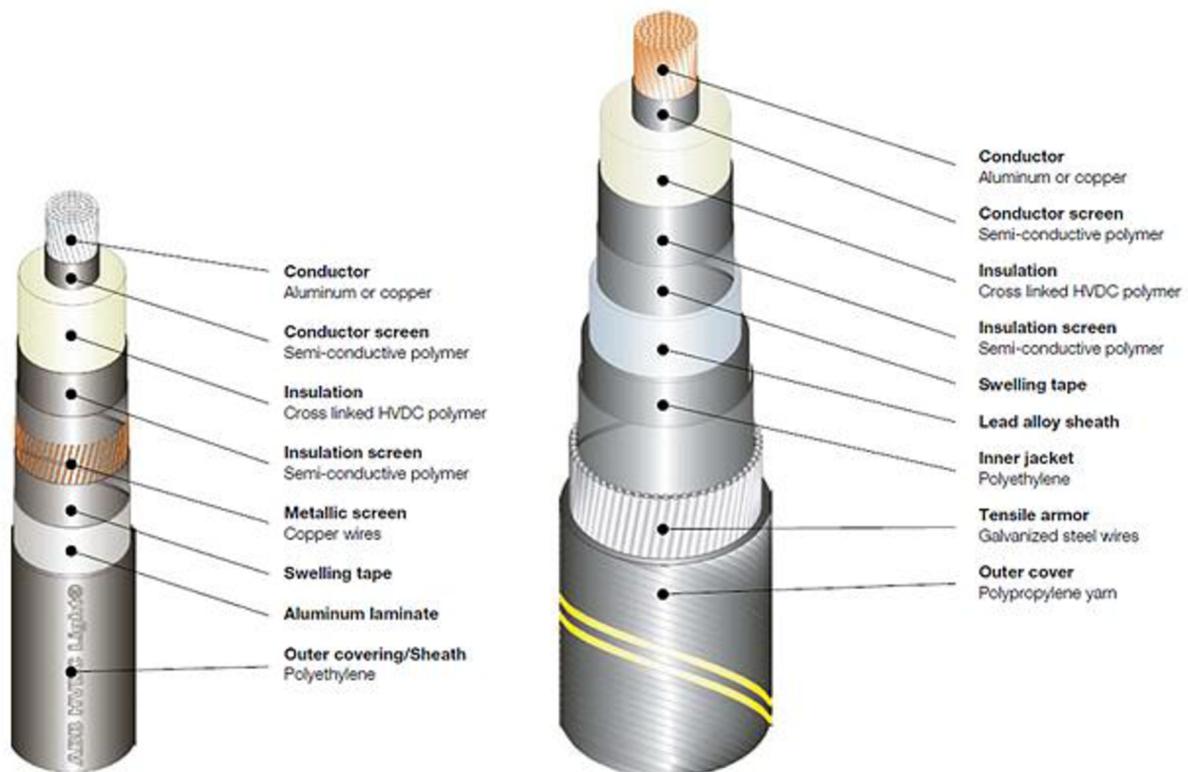


Figure 11 – Underground (left) and submarine (right) XLPE DC cable [26]

armour, covering up to 1700 MW  $\pm$ 320 kV bipolar system. For underground cables aluminium conductor is often used. Cross-section range is the same; copper wire screen is used. For cables with aluminium core, the capacity comparing to copper cable with same cross-section is 25 % lower. Therefore if higher transmission capacity is required, cables with copper conductor are used.

### 2.2.1.5 Other equipment

As mentioned earlier, HVDC systems do not consist only from conductors and converters. AC and DC **filters** are also part of the configuration. While VSC converters are capable of reasonably accurate sine wave generation, thyristor-based converters also generate harmonics. Therefore more robust filters are needed.

For voltage **measurement** ball spark gap or resistor divider can be used, as there is no alternating component. Therefore no distortion of voltage signal caused by parasitic capacities of the resistors will occur. For current measurement shunts are used. The measurement often occurs on valve- or device-basis and is handled by converter control system. The sensors are connected to the processing units via optical fibre [24]. For current measurements innovative OCTs (Optical Current Transformers) can be used as well. OCTs work on principle of Faraday effect – *“the current flowing through a conductor induces a magnetic field that affects the propagation of light traveling through an optical fibre encircling the conductor,”* as Alstom explains [38]. The OCT for DC measurement using reflection Sagnac interferometer was developed in 2008 and successfully field-tested and used at renovated Hokkaido-Honshu HVDC link in Japan. The transformer has attachable sensor of 2 m diameter, so it can be manipulated without disassembling of the cable head. The primary current is rated to DC  $\pm$ 1200 A [39]. Research and development efforts to produce OVT

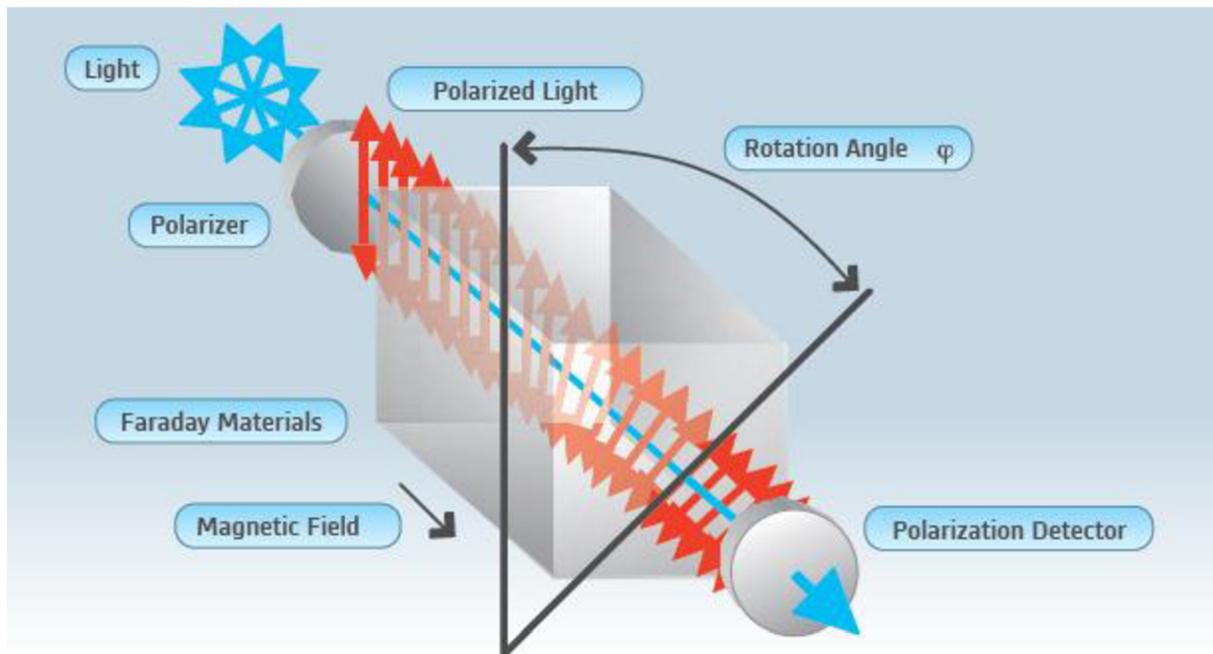


Figure 12 – Principle of Faraday effect usage in Optical Current Transformer [38]

(Optical Voltage Transformer) based on Pockels effect are made – patent for DC OVT is registered [40] and AC OVT prototype has been tested [41].

The question that still has been waiting for a clear answer is lack of proven **DC circuit breaker**. As HVDC systems must provide at least the same level of security, including fault spreading prevention, extensive multi-terminal HVDC grid is unlikely to be operated until DC circuit breaker standard is defined. Unfortunately, low impedances of a HVDC system, which make it felicitous for power transmission, also create friendly environment for fault spreading. Therefore the reaction time and arc extinction time has to be very small.

The arc extinction phenomena in high-power AC circuits are based on natural extinction of the arc at current zero and prevention of a restrike in spite of rising voltage between contacts. The restrike prevention is accomplished using combination of several measures – cooling, replacing ionized particles with unionized particles, usage of resistive inert gas, fast opening of the contacts and division into parts [42]. The problem of a DC circuit breaker is that DC naturally doesn't drop to zero, unlike AC sine wave. Possible solution is to artificially create current zeros through injecting alternating counter-current when the circuit breaker opens and the arc is ignited. The counter-current can be achieved by a parallel resonance circuit; usage of Flux Compression Generator has been considered [43]. However, these mechanical circuit breakers are too slow, as the interruption of the current occurs several tens of ms. Other possibility is a semiconductor based circuit breaker (typically IGBTs), which provides better interruption times, but causes unacceptable losses. Therefore a prototype of a hybrid circuit breaker was introduced by J. Häfner and B. Jacobson [44]. The hybrid circuit breaker uses a bypass over main semiconductor-based circuit breaker, via a fast mechanical disconnecter and an auxiliary circuit breaker, as shown at Figure 13. Under normal operation main circuit breaker is disconnected, this way avoiding the huge commutation losses, and when a fault occurs, auxiliary circuit breaker commutates main circuit breaker, fast disconnecter opens and the current is interrupted in the main circuit breaker.

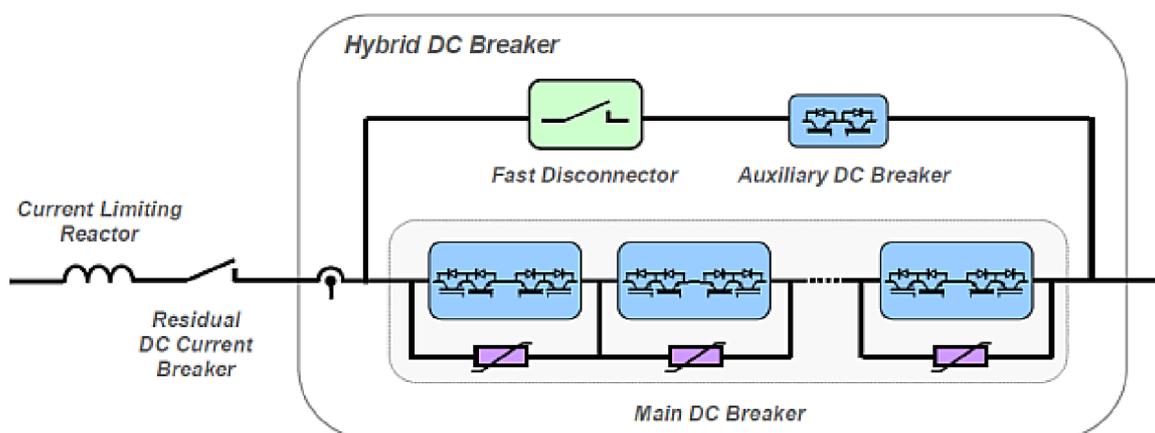


Figure 13 - Modular Hybrid IGBT DC Breaker [44]

Lighting protection of switch stations and lines is conventional using shield wires. As mentioned in chapter 2.2.1.4 “Cables, lines”, it is convenient to consider non-equal chances of lightning strike to conductors.

Switchgear and substations' equipment in general are often carried out as GIS (Gas Insulated Switchgear) and are often used indoor. AIS (Air Insulated Switchgear) require outdoor application due to higher needed space, which is caused by ultra-high voltage levels.

### 2.2.1.6 Experience with HVDC

The direct current transmission is known since late 19<sup>th</sup> century. However, first famous commercial utilization of HVDC as we know it now goes back to 96 km long submarine **Gotland** link, which was commissioned in 1954. In 1970 thyristor valves were used for the first time for power transmission purpose complementing mercury arc valves and enabling increasing capacity of Gotland link to 30 MW. In 1986 the original Gotland 1 link was dismantled after Gotland 2 and 3 were built. Gotland 2 and 3 create a  $\pm 150$  kV 260 MW link and are in operation until present proving lifetime of at least 30 years [45].

In Japan, the first generation of HVDC systems (Shin-Shinano No. 1 FC and Hokkaido-Honshu HVDC Pole 1) were in operation for some 30 years until recent replacement of analogue control systems and thyristor valves. While at Hokkaido-Honshu link no deterioration of thyristors was observed, at Shin-Shinano the current leakage was getting worse [46].

Until 2010, the  $\pm 600$  kV 800 km long **Itaipu** HVDC link was the biggest HVDC link in the world. Both voltage level and power rating were record high for more than 20 years. The link connects 14 000 MW Itaipu hydropower plant at Paraná River with São Paulo region. The first 3150 MW bipole link was commissioned in 1984, starting 1987 the capacity doubled [47]. Thyristor-based Current Source Converters has been producing harmonics and requiring huge amount of reactive power. In total AC filters of 2480 MVar and compensating units of 1790 MVar compensating units are installed. The two bipoles are supplemented by three 765 kV AC lines adding another 6300 MW, thus creating vital part of Brazilian electrical grid and the biggest hybrid corridor in the world. The AC system incorporates of two intermediate AC substations, dividing the link to approximately 300 km long sections. The joint AC/DC Foz do Iguaçu substation is considered also as one of the biggest in the world in terms of size and power. The operation experience after 10 years was very good – the availability has stabilised at more than 99 % per pole per year, maintenance is mostly scheduled, thyristor failure is less than 0.1 % per year, and HVDC system utilization very high [48]. Based on this experience, further projects utilizing HVDC transmission are considered in Brazil including 13 150 MW Tapajós Project, 11 230 MW Belo Monte Project or up to 3000 MW connection to Peru [49]. 6450 MW Madeira River Project is under construction and should be commissioned in 2012. The more than 2500 km long HVDC link between Rio Madeira power plant and São Paulo region will have the capacity of 3150 MW using a  $\pm 600$  kV bipolar system [50].

**Xiangjiaba – Shanghai** is the first large-scale HVDC system utilizing  $\pm 800$  kV technology. The rated power of 6400 MW makes it the most powerful running HVDC link of the world. The line connects Xiangjiaba hydropower plant, part of 18 600 MW Jinsha River Development Project with Shanghai area covering 1980 km. The system was commissioned in July 2010 after just 30 months of construction. Thanks to usage of  $\pm 800$  kV system the losses are at just about 7 %, comparing to estimated 10 % in case of conventional  $\pm 500$  kV system [32]. Due to voltage level of 800 kV and extreme power, design utilizing CSCs was required. The experience with construction and early operation of Xiangjiaba – Shanghai line will be used in construction of 7200 MW Jinping – Sunan line (commissioning scheduled to 2013) in China [51] and multi-terminal 6000 MW link Biswanath Chariali – Alipurduar – Agra in India (operation planned starting 2014 – 2015) [52].

Longest submarine transmission cable in the world is called **NorNed**. The 580 km long 700 MW link connects asynchronous AC transmission grids of Norway and The Netherlands enabling to mutually open electricity markets. The main parts of the bipolar  $\pm 450$  kV system are 12-pulse thyristor-based CSCs and submarine MIND cables with  $700 \text{ mm}^2$  copper core, AC filters of total power 440 MVar, shunt capacitors of totally 402 MVar; no DC filters are required. Advanced technology and thyristor-based converters provide great results – losses are only 3.7 %. Overall investments reached €600 million and the link is in operation since 2008 [53] [54].

Similar technology was used in case of one of the most recently commissioned (April 2011) HVDC link – **BritNed**, which connects AC networks of United Kingdom and The Netherlands. Also BritNed is a  $\pm 450$  kV bipolar HVDC system incorporating 12-pulse thyristor-based Current Source Converters using MIND submarine cables. The link transfers up to 1 GW across 260 km with approximately 3 % losses. The MIND cables with  $1430 \text{ mm}^2$  copper core were laid by 30 special vessels over a period shorter than one year taking €350 million from the overall €600 million budget. The remaining €250 million was spent on converters (approx. €220 million) and other equipment. The construction took from announcement to operation 4 years. BritNed enables market-coupling between Netherlands and UK and is an important step in integration of European electricity market. During first year of operation total flows of 4.9 TWh were recorded [55] [56].

Voltage Source Converters formed by IGBT valves were used for example at 42 km long 330 MW **Cross Sound Cable** in United States for strengthening and increasing stability of New York's electrical grid, or in Australia at **Murraylink** – the longest HVDC underground cable. The link is capable to transmit 200 MW across 180 km, thus enabling trading and drop of prices between Victoria and South Australia territories and boosting stability of both AC grids. The  $\pm 150$  kV bipolar HVDC system is in operation since 2002, after just 22 months of construction. Thanks to low environmental impact and narrow corridor also the right of way obtaining process took much less time [26] [57].

The largest multi-terminal HVDC system at the time is **Québec - New England** HVDC link in Canada and United States. Since 1986 a 170 km  $\pm 450$  kV bipolar HVDC system rated at 690 MW was connecting asynchronous Québec and New England AC grids.

In early 1990s the line was extended to the north to connect La Grande hydropower plant, to the south to supply Boston, and an additional terminal close to Montréal was built; the power was increased to 2000 MW. However, the original terminals were disconnected, therefore since 1992 only a 3-terminal 2000 MW HVDC system of total length of 1480 km is in operation [58].

Every year following HVDC links are commissioned. While in Asia and South America overhead lines are mostly used, for Europe is typical construction of submarine cables. Development and wider deployment of VSC systems is expected, especially for off-shore wind farms applications such as 400 MW **BorWin 1**, which is in operation since 2009. 800 MW **DolWin1** and **900 MW DolWin2** projects should be connected to the grid in 2013, respectively 2015. The off-shore application has been proven at platforms Troll A (88 MW, in operation since 2005) and Valhall (78 MW, commissioned 2011) in North Sea [59].

### 2.2.2 HVAC

HVAC overhead lines and apparatuses at ultra-high voltage **levels 765 kV and above** is considered in context of Super Grids. The state-of-the-art high-voltage technology is nowadays represented by voltage levels of 1100 kV and 1200 kV.

While these voltage levels are in experimental use, the 800 kV AC technology is commercially proven and so far has been introduced in Brazil, Canada, Russia, South Africa, South Korea, United States and Venezuela. While full portfolio of products for 800 kV AC is available, levels 1100 and 1200 kV still require research and development. For example the intention to develop 1200 kV circuit breaker was declared by ABB in April 2012 [60]. Therefore 1200 kV lines built in Japan and Russia are currently operated at lower voltage. Even though 800 kV lines are commercially used since 1980s, the analysis and design techniques were based on extrapolation from lower levels. Adjustments to technical requirements were made only after experience with practical usage. As presented at CIGRE symposium in Bologna, “*extrapolation of the IEC (or IEEE) requirements from 550 and 800 kV to 1100 and 1200 kV would lead to very tall OH line towers and enormous AIS or GIS dimensions,*” [61]. These words are not exaggerated, current transmission tower designs carrying  $2 \times 1200$  kV AC lines exceed height of 100 m.

The need to stabilize power grid, strengthen some links and improve capacity and controllability resulted into development of **FACTS** (Flexible Alternating Current Transmission System) technologies. Most of the problems of AC transmission are closely connected to reactive power. Tasks of FACTS system include therefore reactive power control, together with voltage control, both under various load conditions, thus increasing active power stability and stability of a transmission across long distances. FACTS include both technologies known for decades – mechanically switched compensation units – and new technologies, where significant progress of high-voltage power electronics was required. According to Siemens AG [62], following techniques are used:

- Parallel compensation

- MSCs/MSRs (Mechanically Switched Capacitors/Reactors) use mechanical switches.
- SVC (Static VAR Compensator) uses thyristor valves and enables faster response to changing condition.
- SVC PLUS or STATCOM (Static Compensator) uses IGBT or GTO valves as VSC (Voltage Source Converter) with MMC (Modular Multilevel Converter) design [63].
- Series compensation
  - FSCs (Fixed Series Capacitors) use mechanical switches and spark gaps for protection.
  - TPSCs (Thyristor Protected Series Capacitors) use thyristor valves for switching and protection and enable faster operation recovery.
  - TCSCs (Thyristor Controlled Series Capacitors) use thyristor valves also to control power of the compensation.

For high-power compensation are most suitable SVCs and FSCs covering voltage up to commercially used 765 kV level and providing compensation up to 1000 MVar, respectively 1500 MVar. The principle and connection of SVC is shown at Figure 14.

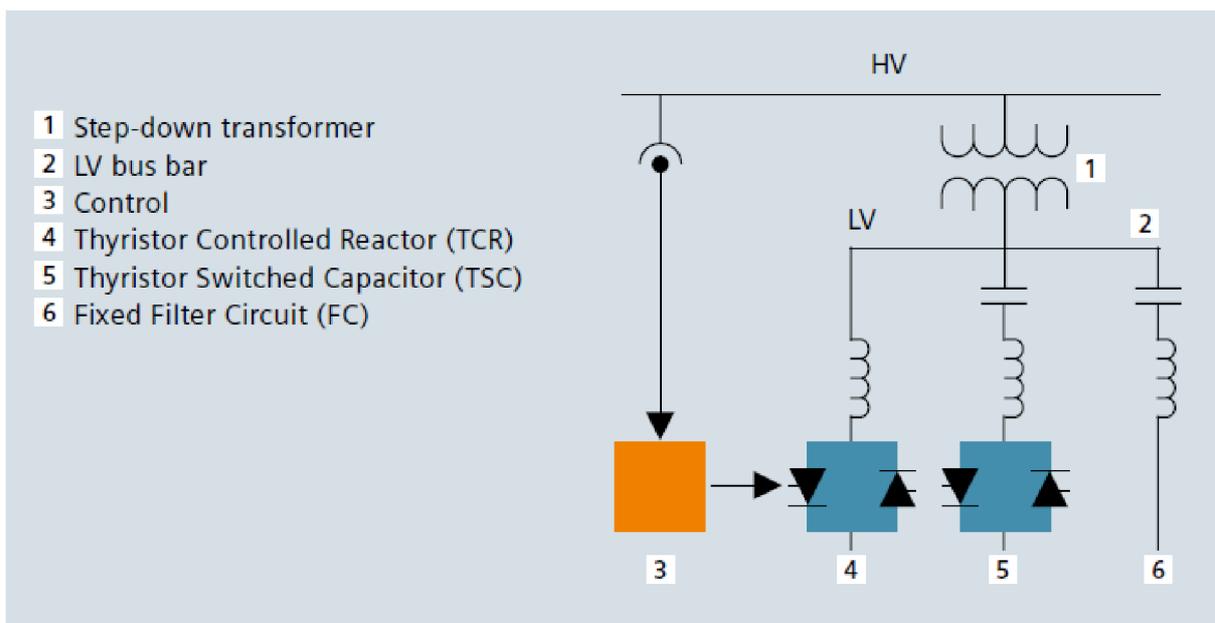


Figure 14 – Simplified scheme of SVC [62]

### 2.2.3 Hybrid systems

One of the biggest disadvantage of HVDC systems are excessive costs of tap converter stations. In cases, where both long distance bulk-power transmission is needed and electricity supply is required by the customers on the way, hybrid systems are a logical alternative. Hybrid systems also seem suitable in cases where transmission capacity of an existing corridor needs to be increased. Since it is highly improbable that construction of a Super Grid

or massive conversion AC grids to HVDC technology will happen in short-time period, hybrid systems need to be investigated, as they are the logical middle step. It's important to pinpoint, that hybrid systems are considered exclusively in context of overhead line transmission.

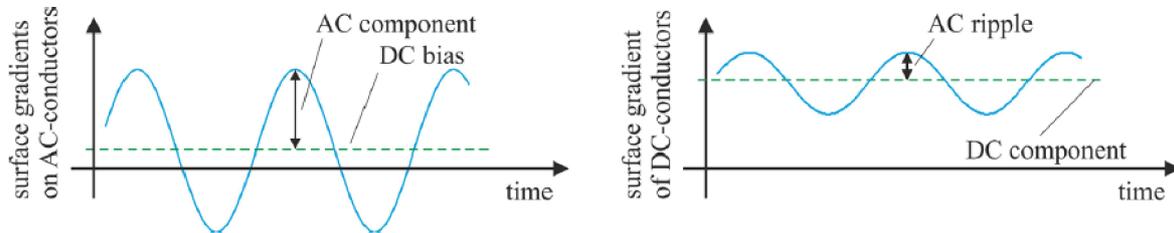


Figure 15 – Coupling of DC system to AC system (left) and vice versa (right) [65]

**Hybrid corridors** are corridors, where both DC and AC lines are present. This arrangement is proven (for example Pacific Intertie) and since the distance between lines is comparing to cross-section of the conductors and distances between conductors of same phase, different phase or pole much larger, the interference is negligible.

The arrangement where AC and DC conductors run at the same set of transmission towers is called **hybrid line** or **hybrid towers**. As there is no practical experience with operation of hybrid towers, research have focused recently on describing possible interference and consequent limitations. The proximity of AC and DC circuits brings several issues for consideration – AC sine wave distortion, modulation of harmonics in DC line (Figure 15), increased effect of corona-discharge and corresponding audible noise and radio interference. Simulation results show, that AC and DC system coupling is not insignificant, yet the parallel operation of both systems at one tower is technically feasible [64]. As for the audible noise, studies show, that critical are positive half-wave peaks and positive pole of DC system. The levels of audible noise differ from layout of towers and placement of conductors. Systems up to  $\pm 600$  kV are capable of operation along with conventional 400 kV AC lines while meeting limits of 60 dB in foul weather and 50 dB in fair weather, if fitting configuration is chosen. The increase of thermally limited transmission capacity of a link  $2 \times 400$  kV AC converted to  $1 \times 400$  kV AC +  $1 \times \pm 500$  kV DC would exceed 50 % [65].

## 2.3 Considered Super Grids

The idea of some sort of superior grid is relatively old, first ideas came usually from United States, as the country surface is large, compact and the power demand is diversified. Situation in Europe was a little bit different – shore is broken and countries are relatively small. The political situation in Europe was very complicated and every country was working on its energy policy separately. This problem has been slowly but firmly reduced with foundation of European Union and its expansion in the time. However, European Union have had very short period of time to show its contribution in energy field so far. Current high voltage transmission system represented mostly by 220 kV and 400 kV AC lines is some kind of such a superior grid. The grid is, however, designed for transmission of hundreds of

megawatts across few hundred kilometres. For massive use of renewable energy sources in large energy parks stronger infrastructure is needed – the concept counts with transmission of gigawatts across thousands of kilometres. It is clear then, that new stronger grid is needed.

Another difference between North America and Europe is in technology, which is intended to use for Super Grid. While in United States both AC and DC concepts are taken under review and both have supporters and critics, in Europe usage of DC system is silently assumed. One of the main reasons was already mentioned – the shore is broken. Also lot of intended power sources are located outside Europe or in the continental shelf, therefore undersea DC cables will be required. Additionally some HVDC infrastructure already exists. Further argument for usage of HVDC in Europe is excessively long permission process for overhead lines, which can take more than 10 years. The submarine links are, on the other hand, built relatively faster.

Generally the costs of Super Grids are significant and seem to be the biggest impediment for its actual development and building. For example, costs for Super Grid linking east and west coast of United States are estimated to reach \$60 billion [66], OffshoreGrid concept in North and Baltic Sea counts with costs of €85 billion [67].

### 2.3.1 DESERTEC

One of the first yet most pioneering concepts was the German-based DESERTEC Foundation's concept introduced in 2003, as shown at Figure 16 – Super Grid concept by DESERTEC. The concept considers Super Grid covering whole Europe with focal point in Mediterranean area. It counts exclusively on renewable energy sources as the only source of



Figure 16 – Super Grid concept by DESERTEC [19]

energy to supply Europe [68]. Special focus is given to large-scale utilization of Concentrated Solar Power plants in North Africa and Middle East. To provide at least some typological diversification massive use of wind power is suggested. Other energy sources are also considered, but have much lower share. The noble idea of emission-free and nuclear-free Europe is based on fact, that otherwise unusable areas receive more power, than humankind is capable to consume. However the concept faces countless of technical and other problems and still remains rather visionary concept than a clear plan, how to secure Europe's energy future.

The lack of any stable, fully controllable base-load sources means, that the supply would be strongly limited by day time and weather conditions. Huge energy storage capacity would be required to overcome these difficulties. Since pumped-storage hydropower plant potential in Europe has been already developed, other means of energy storage would be required. A logical alternative is equipping CSP plants with energy storage working with melted salts. However, the costs for building already costly CSP plants additionally fitted with energy storage systems would further increase investment costs.

Another technical problem is the weakness of European transmission network in terms of transmitting energy from peripheral areas to the industrial centres of energy consumption further into the land. Last two decades have proved that it is almost impossible to build needed new transmission overhead lines at the Europe's mainland due to dense population and lengthy permission process. The only projects which are successfully and on time finished are submarine HVDC links. Even if transition of conventional 400 kV transmission grids to 765 kV AC or hybrid AC/DC lines is carried out, the capacity of the network could still not be sufficient enough.

So far mostly technical problems were discussed. Yet especially the DESERTEC concept faces many problems of a non-technical nature. These problems and recommendations were well-described in paper presented by I. Werenfels and K. Westphal [69]. Basically, the non-technical problems are of following natures:

- financing problems, as both Super Grid and power plants need to be built and the investment costs are gigantic;
- legislative problems regarding missing integrated electricity market and need of massive subsidy of renewable sources;
- unstable political situation and rise of Islamic extremism in North Africa and Middle East, risking energy supply safety if energy sources are concentrated in these regions and loss of vast investments due to nationalization or destruction of energy sources and transmission infrastructure during conflicts;
- conflicts of goals and influence of lobby delaying needed decisions at national and EU political level.

### **2.3.2 OffshoreGrid**

OffshoreGrid is a study elaborating on technical and economic issues of a Super Grid in North and Baltic Sea interconnecting surrounding countries, large-scale offshore wind

parks and hydropower and pumped-storage capacity in Scandinavian countries. The goal is to utilize wind power potential of North Sea area, strengthen connection of electricity consumption centres to the grid, bypass bottlenecks, enable growth of electricity trading and thus lower prices. As the study is funded by EU's Intelligent Energy Europe programme it reflects the targets set by EU in renewable energy domain. The concept develops existing infrastructure, as shown at Figure 17.

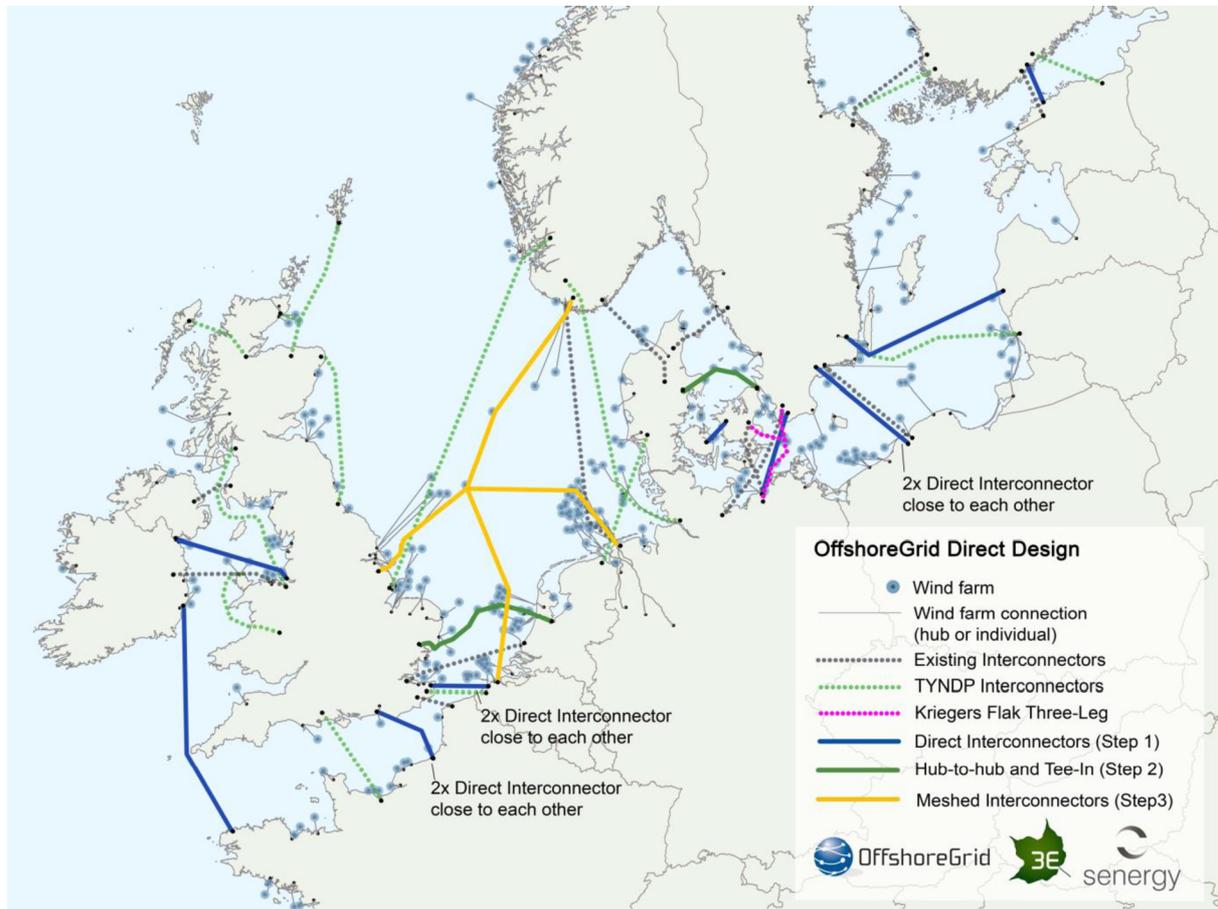


Figure 17 – OffshoreGrid concept including existing and planned connections [76]

The study deals with connecting 126 GW provided by 321 wind power plants and increasing interconnection capacity to 30 GW. Few possible designs are introduced and further elaborated in terms of economic benefits and technical issues. Totally 30 000 km of links is needed with overall budget of approximately €85 billion, in which only construction of transmission infrastructure is covered.

The main idea reducing costs by €14 billion is construction of wind farm hubs for projects locate more than 50 km from shore. While for parks situated closer to the land direct link is recommended, more distant areas could be connected via hub, if more parks is present in a given radius (20 km recommended). Out of 321 evaluated projects, 114 could be connected via hubs. Except costs reduction the benefits are also environmental and logistical, as less submarine cables and AC connection points has to be built. The disadvantage is, that the hub connection to the shore should be properly dimensioned in terms of power when the

first site is built, even though the rest is planned to be built later. The investor then faces risks of unsuccessful investment if the remaining plants are not built. In case more companies plan to build wind parks in a certain area connected to AC grid using single link, problems may arise and concluding contracts describing investments, rights, responsibilities and risks division is recommended. Establishing joint ventures in such cases would be convenient. The best economy for projects using hub connection is reached in power range around 1000 MW; after 2020 increase to 2000 MW is expected.

If a wind park is built far from land and close to a link connecting two countries, under certain circumstances a tee-in configuration might be beneficial. The link must have sufficient capacity to transmit electricity produced in wind farm while considering estimated load factors of both wind farm and interconnector. The primary goal of the link doesn't have to be increased transmission capacity between two countries, but if the plant's power is big enough, the main goal can be to transfer produced electricity to two countries. Then when the load of the plant is low, the link can act as an interconnector. The idea is further explored in hub-to-hub connection configuration. The grid mainly operates as a conventional top-down topology, as it is known from national electrical grids – transmission and distribution of electrical power from sources to places of consumption, which are in this case represented by countries and regions and include pumped-storage hydropower plants. At very low loads the available transmission capacity can be used for energy trading purposes. The idea is based on logical premises and would lead to indisputable reduction of investment costs; also the load factor of the links would be much higher, as well as the security of such grid in sense of n-1 criteria. However, this configuration requires an integrated market of several countries and a very precise weather forecast in order to predict transmission capacity available for trading.

Attractiveness of systemic, integrated solutions lies also in lower risks of low utilization and prolonged payback period, as the profitability doesn't count entirely on electricity trading and construction of following links doesn't affect economy of existing interconnections. There are, however, few problems. From technical point of view, the grid and most of the connections is considered as multi-terminal configuration. This, alongside with need of "start-from-black" ability of offshore sites and need of improved power control at onshore terminals, leads to conclusion that Voltage Source Converters should be used. Further R&D efforts in VSC-based HVDC systems field is required in order to significantly increase rated power, reduce losses and develop reliable and affordable DC circuit breaker. Another problematic field is financing of such integrated solution, as only the costs of transmission infrastructures are several billions of euros and further similar investment is required for construction of wind farms. Both financing by European Union or foundation of a giant joint venture capable to build significant part of discussed 126 GW is highly improbable.

It is needed to pinpoint, that OffshoreGrid is a study, not an initiative or joint venture dedicated to coordinate construction of proposed Super Grid. Even though advantages, disadvantages and feasibility of all suggested arrangements is proven in its Final Report [67] through a set of technical and economical simulations, it is expected, that especially in early

stages (i.e. until 2020) integrated solutions no bigger than hubs will be built. The first hubs are already under construction – HVDC Light links BorWin1 (already in operation), DolWin1 and DolWin2, which were already mentioned in chapter 2.2.1.6 “Experience with HVDC”. Especially DolWin1 with rated power of 800 MW and only 400 MW wind farms assigned can be considered as a pilot hub project.

Since the study counts mainly with submarine cables and offshore plants, obtaining right of ways and overall lengths of construction projects are much shorter than in case of onshore projects. Therefore OffshoreGrid project can play important role in EU’s plan to encourage investments of total €100 billion into electricity transmission infrastructure until 2020.

On the other hand, the OffshoreGrid project alone will not solve the electricity supply problem of Europe, as it helps only well developed countries situated in surroundings of North and Baltic Sea. Implementation of the project without simultaneous investments in other parts of Europe will further increase the differences between “rich north” and “poor south”. The interconnection of OffshoreGrid further to the continent is problematic due to problems with building new transmission capacities, as mentioned earlier in chapter 2.2.1.4 “Cables, lines”. Authors of study realize this fact and discuss OffshoreGrid as a part of a bigger solution, counting on two other main regions requiring interconnections and development of natural gas infrastructure enabling more environmentally friendly power generation in inland consumption centres.

The Offshore concept in general is very detailed and elaborates on particular suggested projects. Despite, or maybe thanks to, fact that the study counts only with development of a limited area and elaborates on non-diversified portfolio of energy sources, the author expects high probability of building proposed Super Grid. It will not happen over a year or decade, but sooner or later, after a progressive development, as particular projects become more profitable and funds are allocated. This statement is supported by recent development with many projects commissioned during past few years (BritNed, NorNed, Storebælt, Fenno Skan) and further under construction or in bidding phase (Skagerrak, NordBalt, East West Interconnector, DolWin1 and DolWin2).

### 2.3.3 Other

The approach of OffshoreGrid is worth following and should be undertaken also elsewhere in Europe and North America, as it gradually increases the required integration of electricity market, spreads the astronomic investments into more years, and requires progressive natural changes instead of revolutionary changes, which are doomed to fail in fossilized environment that has developed in western civilization during past decades.

**MEDGRID**, an alliance formed in July 2010 provides a good example of a concept presented in other part of Europe utilizing other type of power plant – Concentrated Solar Power. The concept works with The Mediterranean Solar Plan to build 20 GW of CSP until 2020. Investment of €6 billion should go to power required power transmission capacity out

of overall budget of €40 - €45 billion. MEDGRID expects, that existing 1.4 GW transmission capacity between North Africa and Europe via Gibraltar strait will be boosted by another 5 GW by construction of HVDC submarine links to Southern Europe. Detailed technical and economical evaluation is being prepared [70]. One of the links leads to Sardinia, where 1 GW SAPEI HVDC link to Italian mainland was put in operation in 2011 [71]. However, reinforcement of Sardinian backbone AC grid is needed in order to cope with import of more



Figure 18 – MEDGRID Concept [70]

than 500 MW from Africa [72]. Comparing to DESERTEC Concept, MEDGRID is more realistic and in the future will focus on assessment of particular projects.

Less developed yet still economically strong countries have proved their ability to pursue megalomaniac projects, as demonstrated on some earlier mentioned projects – hydropower plants Itaipu, Three Gorges or Jinsha River Development Project – as well as corresponding interconnections. The environment is friendlier to revolutionary changes, often thanks to lower population density and fewer rights given to inhabitants of the countries. These rapidly growing regions also do not suffer from chronic excess of energy sources as for example Europe [73]. Every kW of installed power and transmission capacity is needed. Therefore utilization of new projects is almost certain. Excellent examples are **Brazil** and **China**. Both countries operate and plan to build more “HVDC highways” transferring gigawatts of power from huge hydropower plants in the west to large cities on east coast using overhead lines. Especially development in China inevitably leads to Super Grid, as it currently uses 16.6 GW of HVDC links, and further 7.2 GW is planned to be added in 2013.

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### 3 CONCLUSION

Human kind faces a number of challenges. One of the most important is covering growing energy demand while reducing ecological impacts of the production. This bachelor thesis discusses Super Grids Conception as one of the possible solutions.

The author tries to objectively evaluate possibilities for power generation in the future, aiming especially on disproving myths, which are commonly spread in public. Highlights can be summarized as follows.

- In developed countries only deployment of small and micro hydro power plants is expected.
- Power of wind and solar power plants is limited by weather, backup is required.
- Biomass should be used as complementary power source by burning otherwise unusable waste.
- Concentrated Solar Power is interesting, yet still costly alternative. Several designs were introduced, R&D effort is needed to increase profitability.
- With deployment of renewable energy sources, importance of pumped-storage plants grows. Usage of molten salts in combination with CSP is reasonable.
- Nuclear fusion technology is not expected to be ready for power generation usage in upcoming decades.
- Despite accidents, nuclear fission power plants are today the safest power plants in the world. Nuclear power will play a key role in lowering emissions as a base-load source.
- Energy demands of Carbon Capture and Storage systems are significant and profitability is questioned.
- Gas-fired Combined Cycle Power Plants provide increased efficiency and lower environmental impact comparing to other fossil fuel-fired plants.
- Increasing efficiency has been the main motive of development. It has to be ubiquitously applied also in electricity generation, distribution and consumption domains. Electricity and heat cogeneration is convenient as it boosts efficiency of conventional fossil sources.

The real problem is not how to generate required amount of electricity, but how to efficiently transport produced electricity, how to cover changing demand and safely integrate new energy sources. To enable that, two not necessarily exclusive approaches are taken under consideration – distributed Smart Grids and massive Super Grids.

Smart Grids are decentralized grids using two-way communication between its components to optimize energy production, consumption and flow in the grid. Idea is to adjust local demand of electricity and cover it with local (renewable) energy sources, therefore increasing flexibility and predictability of energy supply. A vital part of Smart Grid is Smart Metering system. Italian utility Enel leads this field by equipping 32 million customers with Smart Meters.

Super Grids are wide area high-voltage networks for transporting huge amount of electricity across long distances. While conventional high-voltage AC grids are designed to transport hundreds of megawatts across few hundred kilometres, Super Grids are capable to transfer gigawatts across few thousands kilometres. This is achieved thanks to usage of higher voltage levels and this way lowered losses. Super Grid is supposed to overlay conventional AC grids and act as a superior system increasing stability of local AC grids.

For long distance bulk-power transmission, ability vital for a Super Grid, two technologies are considered – HVDC and HVAC. HVDC offers few benefits:

- ability to connect asynchronous grids,
- better utilization of components,
- for high powers smaller corridors,
- no reactive losses,
- significantly lower total losses, especially if cables are used,
- unlimited distance of transmission,

However, the decision to use AC or DC technology is usually based on economic evaluation. Since the investment costs for terminals including expensive converters are high, for smaller distances, usage of AC technology is beneficial. The break-even point for overhead lines is around 800 km for 3500 MW line and drops with increasing power. For submarine and underground cables the break-even point is reached at much lower distances and powers, as the utilization of cable is 5 times greater and the losses are up to 10 times lower if DC is used. In reality, for important submarine and underground links HVDC technology is used.

There are few configurations of HVDC systems. Bipolar systems are favourable, as they offer low environmental impact, high capacity and possibility to operate at 50 % power in monopolar mode during maintenance of one pole. For Super Grids multi-terminal configuration is important, as it enables to connect more than just two points.

A typical HVDC system consists of lines or cables, converters, control system, AC and DC filters, compensating units, transformers, switchgear and other apparatuses. As of today, the most powerful HVDC link Xianjiaba – Shanghai is in operation at  $\pm 800$  kV level and provides transmission capacity up to 7200 MW across 2000 km.

The state-of-the-art technology is limited by converters. Two main types are available. Current Source Converters consisting of thyristor valves offer high voltage levels, high rated power and lower losses. Voltage Source Converters, which consist of IGBT valves, offer better flexibility, control of reactive power and are more suitable for multi-terminal systems. The voltage of VSC is limited to  $\pm 320$  kV as of today; rated power up to 1500 MW. Both converter types have been commercially proven.

Innovations in overhead lines domain focus on design and construction methods to reduce dimensions and endurance of transmission towers. Usage of underground cables instead of OH lines is discussed. As for measurement an interesting alternative to voltage

dividers and shunt resistors provide Optical Current Transformer (in operation in Japan) and Optical Voltage Transformer (only patent). Development of a DC circuit breaker is needed for construction of meshed grid. Proposed mechanical breakers are too slow, semiconductor-based breakers cause unacceptable losses. Concept of hybrid breaker has to be tested.

Challenges in HVAC field include utilization of voltage levels above 1000 kV and adjusting design methods and techniques to such high voltage. FACTS technologies are required to improve grids' stability. For high-power usage Static VAR Compensators and Fixed Series Compensators are suitable. Conversion of AC corridors to hybrid corridors or lines represents a feasible way, how to increase capacity of existing links.

As described above, most of the technology is already available and commercially proven, both for overhead lines and submarine cables. The problems that Super Grid concepts face are often of a non-technical matter – excessive bureaucracy and financing problems, due to investments in range of up to €100 billion just for transmission infrastructure. Furthermore, legislature changes towards integrated electricity market have to be introduced.

Environment in developing and industrializing countries (e.g. Brazil, India, China) is much friendlier to construction of large-scale power plants and new OH lines corridors as demonstrated on projects built in last decade and further projects under construction (Itaipu, Three Gorges, Jinsha River). Therefore construction of Super Grids is probable.

One of the first and still most visionary Super Grid conceptions was presented by DESERTEC Foundation. The main idea is, that deserts receive more power in few hours, than human kind is capable to consume during whole year. It represents the core mission of a Super Grid – utilization distant otherwise unusable areas for electricity generation; in this case using solar power. However, the concept faces many problems, and neither detailed roadmap nor techno-economic feasibility study has been introduced.

Much more realistic study financed by EU is called OffshoreGrid. It elaborates on construction of a Super Grid in North and Baltic Sea. The study assess over 300 offshore wind park projects and through a set of both technical and economical simulations compares proposed grid designs and scenarios and discusses pros and cons. Investments into transmission infrastructure are estimated to €85 billion for boosting interconnection capacity between participating countries by 30 GW and integrating up to 126 GW of wind power plants. The study incorporates existing infrastructure. The fact, that building a Super Grid is a long-term process is pinpointed together with need of profitability of each project, as it is the main motive of investments. Slow, yet steady and progressive development of this project is expected.

OffshoreGrid alone will not guarantee safe and stable energy supply in Europe, as it focuses only on one area. A €45 billion Super Grid (budget includes both transmission infrastructure and power plants) introduced by MEDGRID should supply Southern Europe with 5 GW of solar power produced in North Africa. The problem how to increase power transmission capacity at the mainland Europe remains to be solved.

In conclusion, Super Grids are valid and viable concepts. Most of the required technology already exists, has been proven over decades, and further R&D effort in order to cut losses and costs is expected. The construction of a Super Grid is therefore matter of time, funds and effort. Political, legislative, administrative and financing problems can be overcome by careful planning, evaluation and focus on profitability of each single project, as shown by OffshoreGrid. Super Grids will play key role in integration of large-scale emission-free sources as a vital part of, possibly SuperSmart, electrical grid of the future.

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