Prospects of Smart Grid Technologies for a Sustainable and Secure Power Supply


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ABSTRACT

Deregulation and privatization are posing new challenges on high voltage transmission and on distribution systems as well. System elements are loaded up to their thermal limits, and power trading with fast varying load patterns is contributing to an increasing congestion. In addition to this, the dramatic global climate developments demand for changes in the way electricity is supplied.

Environmental sustainability and security of power supply are the goals for future grid developments. Estimated global investments required in the energy sector until 2030 are $16 trillion, according to IEA statistics. In Europe alone, some € 500 billion worth of investment will be needed to upgrade the electricity transmission and distribution infrastructure [1]. The electricity network of the future must be secure, cost-effective and environmentally compatible.

KEY WORDS:

Security and Environmental Sustainability of Supply; Smart Grid Technologies; Elimination of Bottlenecks in Transmission; Blackout Prevention; Increase in Transmission Capacity; Reduction in Transmission Losses; Enhanced Grid Access for Regenerative Energy Sources (RES)

1. INTRODUCTION

The vision and enhancement strategy for the future electricity networks is depicted in the program for “SmartGrids”, which was developed within the European Technology Platform (ETP) of the EU in its preparation of 7th Frame Work Program.

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Features of a future “SmartGrid” such as this can be outlined as follows [1]:

- **Flexible**: fulfilling customers’ needs whilst responding to the changes and challenges ahead
- **Accessible**: granting connection access to all network users, particularly for RES and high efficiency local generation with zero or low carbon emissions
- **Reliable**: assuring and improving security and quality of supply
- **Economic**: providing best value through innovation, efficient energy management and ‘level playing field’ competition and regulation

It is worthwhile mentioning that the Smart Grid vision is in the same way applicable to the system developments in other regions of the world. Smart Grids will help achieve a sustainable development. Links will be strengthened across Europe and with other countries where different but complementary renewable resources are to be found. For the interconnections, innovative solutions to avoid congestion and to improve stability will be essential. HVDC (High Voltage Direct Current) provides the necessary features to avoid technical problems in the power systems. It also increases the transmission capacity and system stability very efficiently and helps prevent cascading disturbances. HVDC can also be applied as a hybrid AC-DC solution in synchronous AC systems either as a Back-to-Back for grid power flow control (elimination of congestion and loop flows) or as a long-distance point-to-point transmission.

An increasingly liberalized market will encourage trading opportunities to be identified and developed. Smart Grids is a necessary response to the environmental, social and political demands placed on energy supply [1].

In what follows, the global trends in power markets and the prospects of system developments are depicted, and the outlook for Smart Grid technologies for environmental sustainability and system security is given.

### 2. GLOBAL TRENDS IN POWER MARKETS

In the nearest future we will have to face two mega-trends. One of them is the demographic change. The population development in the world runs asymmetrically. On the one hand, a dramatic growth of population is to be seen in developing and emerging countries. On the other hand, the population in highly developed countries is stagnating. Despite these differences, the expectancy of life increases everywhere.

This increase in population (the number of elderly people in particular) poses great challenges to the worldwide infrastructure. Water, power supply, health service, mobility – these are only some of the notions which cross one’s mind directly.

The second mega-trend to be mentioned is the urbanization with its dramatic growth worldwide. In less than two years more people will be living in cities than in the country. Megacities keep on growing. Already today they are the driving force of the world’s economy: Tokyo e.g. is the largest city in the world, its population is 35 m people and it is responsible for over 40 % of the Japanese economic performance. Another example is Los Angeles with its 16 m citizens and a share of 11 % in the US-economy; or Paris with its 10 m citizens and 30 % of the French gross domestic product.

Both of these mega-trends make the demand for worldwide infrastructure grow. Fig. 1 depicts the development of world population and power consumption up to 2020. The figure shows that particularly in developing and emerging countries the increase is lopsided. Fig. 2 highlights these phenomenal developments in China’s megacity Shanghai.

This development goes hand in hand with a continuous reduction in non-renewable energy resources. The resources of conventional as well as non-conventional oil are gradually coming to an end. Other energy sources are also running short, ref. to Fig. 3. So, the challenge is as follows: for the needs of a dramatically growing world population with the simultaneous reduction in fossil power sources, a
proper way must be found to provide reliable and clean power. This must be done in the most economical way, for a lot of economies, in the emerging regions in particular, cannot afford expensive environmentally compatible technologies.

Fig. 1: Development of World Population and Power Consumption - 1980 to 2020

Financial District Pudong, Shanghai

Fig. 2: Development of Megacities – Example Shanghai, China

Fig. 3: Decreasing Energy Resources
Consequently, we have to deal with an area of conflicts between reliability of supply, environmental sustainability as well as economic efficiency [10]. The combination of these three tasks can be solved with the help of ideas, intelligent solutions as well as innovative technologies, which is the today’s and tomorrow’s challenge for the planning engineers worldwide.

This is exactly what Siemens has been doing over the last 160 years. In the field of power supply, the founder of the company, Werner von Siemens, launched the electrical engineering with his invention of the dynamo-electric principle in 1866. Since that time electric power supply has established itself on all the continents, however, with an unequal degree of distribution. Depending on the degree of development and power consumption, different regions have very different system requirements, ref. to Fig. 4.

In developing countries, the main task is to provide local power supply, e.g. by means of developing small isolated networks.

Emerging countries have a dramatic growth of power demand. Enormous amounts of power must be transmitted to large industrial regions, partly over long distances, that is, from large hydro power plants upcountry to coastal regions which involves high investments. The demand for power is growing as well. Higher voltage levels are needed, as well as long-distance transmission by means of FACTS and HVDC.

During the transition, the newly industrialized countries need energy automation, life-time extension of the system components, such as transformers and substations. Higher investments in distribution systems are essential as well. Decentralized power supplies, e.g. wind farms, are coming up.

Industrialized countries in their turn have to struggle against transmission bottlenecks, caused, among other factors, by increase in power trading. At the same time, the demand for a high reliability of power supply, high power quality and, last but not least, clean energy increase in these countries. In spite of all the different requirements one challenge remains the same for all: sustainability of power
supply must be provided. Our resources on the Earth are limited, as shown in Fig. 3, and the global climate is very sensitive to environmental influences. The global industrialization with its ongoing CO₂ production is causing dramatic changes in the climate developments, ref. to Fig. 5.

![Carbon Dioxide Variations in the Air](image)

**Fig. 5: CO₂ Increase due to Human Influence is much higher than Natural Fluctuation**

There is no ready-made solution to this problem. The situation in different countries and regions is too complex. An appropriate approach is, however, obvious: power generation, transmission, distribution and consumption must be organized efficiently.

The approach of the EU’s “SmartGrid” vision is an important step in the direction of environmental sustainability of power supply, and new transmission technologies can effectively help reduce losses and CO₂ emissions.

3. PROSPECTS OF POWER SYSTEM DEVELOPMENT

The development of electric power supply began more than one hundred years ago. Residential areas and neighboring establishments were at first supplied with DC via short lines. At the end of the 19th century, AC transmission was introduced, using higher voltages to transmit power from remote power stations to the consumers.

In Europe, 400 kV became the highest voltage level, in Far-East countries mostly 550 kV, and in America 550 kV and 765 kV. The 1150 kV voltage level was anticipated in some countries in the past, and some test lines have already been built. Fig. 6 and 7 depict these developments and prospects.

Due to an increased demand for energy and the construction of new generation plants, first built close and then at remote locations from the load centers, the size and complexity of power systems all over the world have grown. Power systems have been extended by applying interconnections to the neighboring systems in order to achieve technical and economical advantages. Large systems covering parts of or even whole continents, came into existence, to gain well known advantages, e.g. the possibility to use larger and more economical power plants, reduction of reserve capacity in the
systems, utilization of the most efficient energy resources, as well as achieving an increase in system reliability.

In the future of liberalized power markets, the following advantages will become even more important: pooling large power generation stations, sharing spinning reserve and using most economic energy resources, and considering ecological constraints, such as the use of large nuclear and hydro power stations at suitable locations, solar energy from desert areas and embedding big offshore wind farms.

Examples of large AC interconnections are systems in North America, Brazil, China and India, as well as in Europe (UCTE - installed capacity 530 GW) and Russia (IPS/UPS - 315 GW), which are planned to be interconnected in the future.

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- Voltage Levels of 735 kV to 765 kV AC were introduced in the following Countries:
  - Canada, Brazil, Russia (USSR), South Africa, South Korea, U.S.A. and Venezuela
- UHV Transmission Lines (1,000 kV and above) were built in Russia and Japan
  - Ekibastuz – Kokchetav (500 km)
  - Kokchetav – Kustanay (400 km)
  - Minami – Niigata / Nishi – Gunma (200 km)
  - Kita – Tochigi / Minami – Iwaki (250 km)
- However, today these UHV Transmission Lines are operated at 500 kV

![Fig. 6: Development of AC Transmission – Milestones and Prospects](image)

Fig. 6: Development of AC Transmission – Milestones and Prospects

However, some Countries will finally “go” ≥ 1 GV

![Fig. 7: Development of EHV and UHV AC Transmission](image)

Fig. 7: Development of EHV and UHV AC Transmission

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It is, however, a crucial issue that with an increasing size of the interconnected systems (ref. to Fig. 8), the advantages diminish. There are both technical and economical limitations in the interconnection if the energy has to be transmitted over extremely long distances through the interconnected synchronous AC systems. These limitations are related to problems with low frequency inter-area oscillations ([6], Fig. 8a), voltage quality and load flow. This is, for example, the case in the UCTE system, where the 400 kV voltage level is in fact too low for large cross-border and inter-area power

Fig. 8: UCTE – Steps a) & b) for Interconnection of Zones 1, 2 and further Options c)

- Inter-Area Oscillations with Magnitudes up to 1000 MW
- Damping Measures necessary
exchange. Bottlenecks are already spotted (Fig. 9, NTC values) and, for an increase in power transfer, advanced solutions must be applied.

Fig. 9: European Power Systems - Bottlenecks in UCTE

In deregulated markets, the loading of existing power systems will further increase, leading to bottlenecks and reliability problems. System enhancement will be essential to balance the load flow and to get more power out of the existing grid. Large blackouts in America and Europe confirmed clearly that the favorable close electrical coupling of the neighboring systems might also include the risk of uncontrollable cascading effects in large and heavily loaded synchronous AC systems [9].

Fig. 10: Large Power System Interconnections - Benefits of Hybrid Solutions
Therefore, the strategies for the development of large power systems go clearly in the direction of hybrid transmissions, consisting of DC and AC interconnections, including FACTS. Hybrid interconnected systems such as these offer significant advantages, in terms of technology, cost savings and reliability [9, 11, 12, 13, 19, 20].

Fig. 10 shows schematically a hybrid system with HVDC and FACTS. Power exchange in the neighboring areas of interconnected systems can be achieved by means of AC links, preferably with FACTS to increase transmission capacity and stability. The transmission of large power blocks over long distances should, however, be realized by means of HVDC links directly to the locations of power demand [12].

4. SECURITY OF SUPPLY – LESSONS LEARNED FROM THE BLACKOUTS

In Fig. 11, a summary of the US-Canada Blackout on August 14, 2003 is shown. In Fig. 11 a) a view on the affected area is given and the satellite photos show the situation before and after the events. The figure indicates that the Québec’s system in Canada was not affected due to its DC interconnections to the US, whereas Ontario (synchronous interconnection) was fully “joining” the cascade. The reasons why Québec “survived” the Blackout are very clear:

- Québec’s major Interconnections to the affected Areas are DC-Links
- These DC-Links are like a Firewall against Cascading Events
- They split the System at the right Point on the right Time, whenever required
- Therefore, Québec was “saved”
- Furthermore, the DCs assisted the US-System Restoration by means of “Power Injection”

Fig. 11b) depicts the results of a study on the related transmission systems, published in May 2002. It can be seen that load flow in the system is not well matching the design criteria, ref. to the “hot lines”, shown in red color. In the upper right-hand corner of the figure, one of the later Blackout events with “giant” loop flows is attached which occurred just in the same area under investigation one year before.

Fig. 12 shows that the probability of large Blackouts is much higher than calculated by mathematical modeling, particularly when the related amount of power outage is very large. The reasons for this result are indicated in the figure. This means that, when once the cascading sequence is started, it is mostly difficult or even impossible to stop it, unless the direct causes are eliminated by means of investments into the grid and by an enhanced training of the system operators for better handling of the emergency situations.

For these reasons, further Blackouts occurred in the same year. The largest was the Italian Blackout, six weeks after the US-Canada events. It was initiated by a line trip in Switzerland. Reconnection of the line after the fault was not possible due to a very large phase angle difference (about 60 degrees, leading to blocking of the Synchro-Check device). 20 min later a second line tripped, followed by a fast trip-sequence of all interconnecting lines to Italy due to overload. During this sequence, the frequency in Italy ramped down for 47.5 Hz within 2.5 min, and the whole country blacked-out.

Several reasons were reported: wrong actions of the operators in Italy (insufficient load rejection) and a very high power import from the neighboring countries in general. Indeed, during the night from Saturday to Sunday, the scheduled power import was 6.4 GW - this is 24 % of the total consumption at that time (27 GW; EURELECTRIC Task Force Final Report 06-2004). The real power import was
even higher (6.7 GW; possibly due to the country-wide celebration of what is known as “White Night”), ref. to Fig. 13.

**Fig. 11: Blackouts 2003 - Example United States**

a) The Blackout Area - and a Satellite View

b) Congestion and Loop Flows - Forecasting Studies and Cascading Events

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**System Enhancement necessary!**


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**Problems only in the synchronous interconnected Systems**


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** Québec’s HVDCs assist in Power Supply and System Restoration**

Source: EPRI 2003
In Table 1, a summary of the root causes for the Italian Blackout is given. It can be concluded, that the existing power systems from their topology are not designed for wide-area energy trading. The grids are close to their limits. Restructuring will be essential, and the grids must achieve “Smart” features, as stated before.

This is also confirmed by the recent large blackout on 4.11.2006 which affected eight EU countries (Fig. 14). It has highlighted the fact that Continental Europe is already behaving in some respects as a single power system, but with a network not designed accordingly. Europe's power system (including its network infrastructure) has to be planned, built and operated for the consumers it will serve. Identifying, planning and building this infrastructure in liberalized markets is an ongoing process that requires regular monitoring and coordination between market actors [1].

The electric power supply is essential for life of a society, like the blood in the body. Without power supply there are devastating consequences for daily life: breakdown of public transportation systems, traffic jams, computer outages as well as standstill in factories, shopping malls, hospitals etc.
### Lessons Learned:

Power Systems have not been designed for “wide-Area” Energy Trading with daily varying load patterns.

#### Table 1: Summary of Root Causes for the Italian Blackout and Action Plan

**UCTE Interim Report 10-27-2003**

<table>
<thead>
<tr>
<th>Identified root cause</th>
<th>Impact on events</th>
<th>Origin of root cause</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Unsuccessful re-closing of the Balkan interconnector due to a too high phase angle difference.</td>
<td>Decisive</td>
<td>Large phase angle due to poor lines and network topology</td>
<td>Study settings of concerned protection devices. Reassess possible consequences for NTC to Italy. Coordination of emergency procedures.</td>
</tr>
<tr>
<td>2 Lacking a sense of urgency regarding the San Bernardino line overload and call for inadequate countermeasures in Italy.</td>
<td>Decisive</td>
<td>Human factor</td>
<td>Operator training for emergency procedures. Reassess acceptable overload margins. Study real-time monitoring of transmission line capacities.</td>
</tr>
<tr>
<td>3 Angle instability and voltage collapse in Italy.</td>
<td>General tendency towards grid instability close to its limits</td>
<td>Not the cause to the origin of the events but was the cause that successful island operation in Italy often saw its disconnection did not succeed.</td>
<td>Further studies necessary on how to integrate stability issues in UCTE security &amp; reliability policy.</td>
</tr>
<tr>
<td>4 Right-of-way maintenance practices.</td>
<td>Possible</td>
<td>Operational practices</td>
<td>Perform technical audit. If necessary, improve tree cutting practices.</td>
</tr>
</tbody>
</table>

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**A Key-Issue in many Power Systems today:**

**The Grids are “close to their Limits”**

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Fig. 14: European Power System Disturbance on 4th November 2006

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Source: RTE

Presented at CEPSI, 6-10 November, 2006, Mumbai - India
In Fig. 15, a conclusion on the today’s power system limitations is given and the solutions are outlined.

5. USE OF SMART GRID TECHNOLOGIES FOR SYSTEM ENHANCEMENT AND GRID INTERCONNECTION

In the second half of the last century, high power HVDC transmission technology was introduced, offering new dimensions for long distance transmission. This development started with the transmission of power in a range of a few hundred MW and was continuously increased. Transmission ratings of 3 GW over large distances with only one bipolar DC line are state-of-the-art in many grids today. World’s first 800 kV DC project in China has a transmission rating of 5 GW (ref. to section 6.) and further projects with 6 GW or even higher are at the planning stage. In general, for transmission distances above 700 km, DC transmission is more economical than AC transmission ($\geq 1000$ MW). Power transmission of up to 600 - 800 MW over distances of about 300 km has already been achieved with submarine cables, and cable transmission lengths of up to about 1,000 km are at the planning stage. Due to these developments, HVDC became a mature and reliable technology [3, 12, 13]. During the development of HVDC, different kinds of applications were carried out. They are shown schematically in Fig. 16. The first commercial applications were HVDC sea cable transmissions, because AC cable transmission over more than 80-120 km is technically not feasible due to reactive power limitations. Then, long distance HVDC transmissions with overhead lines were built as they are more economical than transmissions with AC lines. To interconnect systems operating at different frequencies, Back-to-Back (B2B) schemes were applied. B2B converters can also be connected to long AC lines (Fig. 16a). A further application of HVDC transmission which is very important for the future is its integration into the complex interconnected AC system (Fig. 16c). The reasons for these hybrid solutions are basically lower transmission costs as well as the possibility of bypassing heavily loaded AC systems [12].

Typical configurations of HVDC are depicted in Fig. 17. The major benefit of the HVDC, both B2B and LDT, is its incorporated ability of fault-current blocking which serves as an automatic firewall for Blackout prevention in case of cascading events, which is not possible with synchronous AC links.
HVDC PLUS (Fig. 18) is the preferred technology for interconnection of islanded grids to the power system, such as off-shore wind farms. This technology provides the “Black-Start” feature by means of self-commutated voltage-sourced converters (VSC). Voltage-sourced converters do not need a “driving” system voltage; they can build up a 3-phase AC voltage via the DC voltage at the cable end, supplied from the converter at the main grid. Siemens uses an innovative Modular Multilevel Converter (MMC) technology for HVDC PLUS with low switching frequencies. Therefore only small or even nor filters are required at the AC side of the converter transformers. Fig. 18 summarizes the advantages in a comprehensive way. The specific features of MMC are explained in details in [21].

Since the 1960s, Flexible AC Transmission Systems have been developed to a mature technology with high power ratings [4, 5]. The technology, proven in various applications, became mature and highly reliable. FACTS, based on power electronics, have been developed to improve the performance of
weak AC Systems and to make long distance AC transmission feasible [4]. FACTS can also help solve technical problems in the interconnected power systems. FACTS are applicable in parallel connection (SVC, Static VAR Compensator - STATCOM, Static Synchronous Compensator), in series connection (FSC, Fixed Series Compensation - TCSC/TPSC, Thyristor Controlled/Protected Series Compensation - S³C, Solid-State Series Compensator), or in combination of both (UPFC, Unified Power Flow Controller - CSC, Convertible Static Compensator) to control load flow and to improve dynamic conditions. Fig. 19 and 20 show the basic configurations of FACTS.

Fig. 18: DC with VSC – HVDC PLUS, the Power Link Universal System

**FACTS - Flexible AC Transmission Systems: Support of Power Flow**
- SVC – Static Var Compensator* (The Standard of Shunt Compensation)
- SVC PLUS (= STATCOM - Static Synchr. Compensator, with VSC)
- FSC – Fixed Series Compensation
- TCSC – Thyristor Controlled Series Compensation*
- TPSC – Thyristor Protected Series Compensation**
- GPFC – Grid Power Flow Controller* (FACTS-B2B)
- UPFC – Unified Power Flow Controller (with VSC)

* with LT Thyristors
** with special High Power LT Thyristors

and SCCL ** for Short-Circuit Current Limitation

Fig. 19: Transmission Solutions with FACTS
Benefits:
- Improvement of Voltage Quality
- Increased Stability

Fixed Series Compensation:
- Increase in Transmission Capacity

Controlled Series Compensation:
- Damping of Power Oscillations
- Load-Flow Control
- Mitigation of SSR

Fig. 20: Main FACTS Configurations (ref. to Text)
  a) SVC for Parallel Compensation
  b) TCSC/TPSC and FSC for Series Compensation
GPF C is a special DC back-to-back link, which is designed for fast power and voltage control at both terminals [14]. In this manner, GPF C is a “FACTS B2B”, which is less complex and less expensive than the UPFC.

Rating of SVCs can go up to 800 MVar, series FACTS devices are installed on 550 and 735 kV levels to increase the line transmission capacity up to several GW. Recent developments are the TPSC (Thyristor Protected Series Compensation) and the Short-Circuit Current Limiter (SCCL), both innovative solutions using special high power thyristor technology [14]. The world’s biggest FACTS project with Series Compensation (TCSC/FSC) is at Purane and Gorakhpur in India with a total rating of 1.7 GVAr. Fig. 21 depicts the Siemens high power electronic applications worldwide. In the figure the number and the expansion in large HVDC long-distance transmission projects are also indicated.

In India, there are similar prospects for UHV DC as in China due to the large extension of the grid [15, 16]. The road-map for India’s hybrid bulk power grid developments is depicted in Fig. 22. India’s energy growth is about 8-9 % per annum, with an installed generation capacity of 124 GW in 2006 (92 GW peak load demand). The installed generation capacity is expected to increase to 333 GW by 2017 [20].

Fig. 23 depicts how the ideas of hybrid bulk power interconnections are reflected in China's UHV grid developments [19]. The focus is on interconnection of 7 large inter-provincial grids of the Northern, Central and Southern systems via three bulk power corridors which will built up a redundant “backbone” for the whole grid. Each corridor is planned for about 20 GW transmission capacity which shall be implemented with both AC and DC transmission lines with ratings of 4-10 GW each (at +/- 800 kV DC and 1000 kV AC, ref. to the figure). Therefore, each corridor will have a set-up with 2-3

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Fig. 21: FACTS & HVDC worldwide – Example Siemens (ref. to Text)

Bulk Power UHV AC and DC transmission schemes over distances of more than 2000 km are currently under planning for the connection of various large hydropower stations in China [17, 18]. Ultra high DC (up to 800 kV) and ultra high AC (1000 kV) are the preferred voltage levels for these applications to keep the transmission losses as low as possible.

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systems for redundancy reasons. With these ideas, China envisages a total amount of about 900 GW installed generation capacity by 2020. For comparison, UCTE and IPS/UPS together sum up to 850 GW today.

**HVDC SYSTEMS BY 2011-12**

![HVDC SYSTEMS BY 2011-12](image)

** Development of Chicken Neck Area**

50 GW Hybrid:

- ≈ 10 GW AC
- ≈ 40 GW DC

**Fig. 22: Grid Developments in India [8, 9]**

- a) System Overview – including the “Chicken Neck Area”
- b) Hybrid Solutions in the Chicken Neck – including UHV DC

Source: "Brazil-India-China Summit Meeting on HVDC & Hybrid Systems – Planning and Engineering Issues", July 2006, Rio de Janeiro, Brazil
The benefits of hybrid power system interconnections as large as these are clear:

- Increase in transmission distance and reduction in losses - with UHV
- HVDC serves as stability booster and firewall against large blackouts
- Use of the most economical energy resources - far from load centers
- Sharing of loads and reserve capacity
- Renewable energy resources, e.g. large wind farms and solar fields can be integrated much more easily

However, with the 1000 kV AC lines there are also some stability constraints: if for example such an AC line of this kind with up to 10 GW transmission capacity is lost during faults, large inter-area oscillations might occur. For this reason, additional FACTS controllers for power oscillation damping and stability support are in discussion.

The idea of embedding huge amounts of wind energy in the German grid by using HVDC, FACTS and GIL (Gas Insulated Lines) is depicted in Fig. 24. The goal is a significant CO₂ reduction through the replacement of conventional energy sources by renewable energies, mainly offshore wind farms [2]. Power output of wind generation can vary fast in a wide range, depending on the weather conditions. Therefore, a sufficiently large amount of controlling power from the network is required to substitute the positive or negative deviation of actual wind power infeed to the scheduled wind power amount. Fig. 25 shows a typical example of the conditions, as measured in 2003. Wind power infeed and the regional network load during a week of maximum load in the E.ON control area are plotted.

The relation between consumption and supply in this control area is illustrated in the figure. In the northern areas of the German grid, the transmission capacity is already at its limits, especially during times with low load and high wind power generation [7].

An efficient alternative for the connection of offshore wind farms is the integration of HVDC long distance transmission links into the synchronous AC system as schematically shown in Fig. 26 [13].
Fig. 24: Integration of large Offshore Wind Farms by means of GIL, FACTS and HVDC - A Smart Grid Solution

- **Long-term: 30 - 50 GW**
  - incl. Baltic Sea & On-Shore
  - GIL in Tunnel to avoid 40-60 Cables nearby the Coasts

**Fig. 25:** Network Load and aggregated Wind Power Generation during a Week of maximum Load in the E.ON Grid

**Problems with Wind Power Generation:**
- Wind Generation varies strongly
- It can not follow the Load Requirements

**Source:** E.ON - 2003
6. PROJECTS WITH HVDC AND FACTS – FOR ENVIRONMENTAL SUSTAINABILITY AND SECURITY OF SUPPLY

6.1. Bulk Power DC Transmission in China

The 3000 MW +/-500kV bipolar Gui-Guang HVDC system (Fig. 27) with a transmission distance of 980 km was built to increase the transmission capacity from west to east [12]. It is integrated into the large AC interconnected system. In the same system there is also an already existing HVDC scheme in operation. Both DC systems operate in parallel with AC transmission in this grid.

**Benefits of such a Solution:**
- Load Sharing
- Generation Reserve Sharing

**Installed Generation Capacity: 120 GW (2006)**

**Fig. 26: Use of HVDC Long Distance Transmission for Wind Farm Grid Access**

**Fig. 27: Highlights of the Gui-Guang HVDC Transmission Project**
In addition to this, Fixed Series Compensation (FSC) and Thyristor Controlled Series Compensation were used in the system. Due to long transmission distances, the system experiences severe power oscillations after faults, close to the stability limits. With its ability to damp power oscillations, HVDC plays an important role for reliable operation of the system [13].

In June 2007, Siemens received the order from China Southern Power Grid Company, Guangzhou, to construct a high-voltage DC transmission (HVDC) system between the province of Yunnan in the southwest of China and the province of Guangdong on the south coast of the country together with the Chinese partners. The system will be the first in the world to transmit electricity at a DC voltage of +/- 800 kV. At the same time, this project with a power transmission capacity of 5000 MW will be the long-distance HVDC link with the world’s highest power capacity which has ever been achieved. The additional electric power from Yunnan is intended to supply the rapidly growing industrial region of the Pearl River delta in the province of Guangdong and the megacities of Guangzhou and Shenzhen. In the future, the electricity generated by several hydro-electric power plants will be transported from Yunnan via 1,400 km to Guangzhou over this long-distance HVDC link. This HVDC link will save the CO2 emissions of more than 30 million tons a year. This corresponds to the amount of harmful gas which would be produced otherwise, for example through the construction of additional conventional fossil power plants in the province of Guangdong to serve the regional grid.

Fig. 28 gives an overview of this world’s biggest HVDC project.

Fig. 28: World’s first 800 kV HVDC – in China Southern Power Grid

6.2. Security of Supply for the Mega-Cities: Example HVDC Project Neptune – USA

After the 2003 blackout in the United States, new projects are gradually coming up in order to enhance the system security.

One example is the Neptune HVDC project. Siemens PTD was awarded a contract by Neptune Regional Transmission System LLC (RTS) in Fairfield, Connecticut, to construct an HVDC transmission link between Sayreville, New Jersey and Long Island, New York. As new overhead lines can not be built in this densely populated area, power should be brought directly to Long Island by HVDC cable transmission, by-passing the AC sub-transmission network. For various reasons, environmental protection in particular, it was decided not to build a new power plant on Long Island.
near the city in order to cover the power demand of Long Island with its districts Queens and Brooklyn which is particularly high in summer. The Neptune HVDC interconnection is an environmentally compatible, cost-effective solution which will help meet these future needs. The low-loss power transmission provides access to various energy resources, including renewables. The interconnection is carried out via a combination of submarine and subterranean cable directly to the network of Nassau County which borders on the city area of New York.

Neptune RTS was established to develop and commercially operate power supply projects in the United States. By delivering a complete package of supply, installation, service and operation from one single source, Siemens is providing seamless coverage of the customer’s needs. The availability of this combined expertise fulfills the prerequisites for financing these kinds of complex supply projects through the free investment market.

Siemens and Neptune RTS were developing the project over three years to prepare it for implementation. In addition to providing technological expertise, studies, and engineering services, Siemens also supported its customer in the project’s approval process.


Fig. 29: Highlights of Neptune HVDC Project - USA

In Fig. 29, highlights of this innovative project that are typical for future integration of HVDC into a complex synchronous AC system are depicted.

During trial operation, 2 weeks ahead of schedule, Neptune HVDC proved its Blackout prevention capability in a very impressive way. On June 27, 2007, a Blackout occurred in New York City. Over 380,000 people were without electricity in Manhattan and Bronx for up to one hour, subway came to standstill and traffic lights were out of operation. In this situation, Neptune HVDC successfully supported the power supply of Long Island and due to this, 700,000 households could be saved there.

6.3. Green Power with Basslink HVDC – Australia

Fig. 30 gives an overview of the Basslink project in Australia, which transmits electric power from wind- and hydro sources very cost-efficiently from George Town in Tasmania to Loy Yang in Victoria and the same way back.
This happens by means of HVDC via a combination of submarine cable (with 295 km the longest submarine cable in the world up to now), subterranean cables (8 km for reasons of landscape protection) and overhead lines over a total transmission distance of 370 km. The nominal power is 500 MW at a DC Voltage of 400 kV and a current of 1250 A. The overload capacity of the transmission system is 600 MW during 10 hours per day.

Fig. 30: Basslink HVDC – Sustainability of a “Smart” and flexible Grid
Both Victoria and Tasmania profit from the interconnection of their networks:

During times of peak load Tasmania delivers “green energy” from its hydro power stations to Victoria, while Tasmania can cover its base load demands out of the grid of Victoria during dry seasons when the hydro-reservoirs are not sufficiently filled. Furthermore, the island of Tasmania receives access to the power market of the Australian continent.

Tasmania intends to install additional wind farms to increase its share in regenerative energy production. The figure shows that hydro power is perfectly suitable to be supplemented with the rather “fuzzy” wind energy – in terms of base load as well as through its ability to store energy for peak load demands. So far, the DC link can do much more to reduce CO₂ through the combined use of regenerative energies.

6.4. HVDC Transmissions East-South Interconnector and Ballia-Bhiwadi - India

The HVDC East-South interconnection (commercial operation in 2003) uses both advantages, the avoidance of transmission of additional power through the AC system and the interconnection of power areas which can not be operated synchronously. Fig. 31 shows the geographical location of the DC Interconnector and its main data. A view of the HVDC northern terminal in the state of Orissa is given in Fig. 32.

![Geographic Map and Main Data of Indian East-South Interconnector](image)

Fig. 31: Geographic Map and Main Data of Indian East-South Interconnector

In April 2006, Siemens was awarded an order by Powergrid Corporation of India to increase the transmission capacity of the East-South DC transmission from 2000 MW to 2500 MW. As the upgrade is now completed, it is possible to make maximum use of the system’s overload capacity. To increase the capacity of the link, the Siemens experts have developed a solution known as Relative Aging Indication and Load Factor Limitation (RAI & LFL). By these means, it is possible to utilize the overload capacity of the system more effectively without having to install additional thyristors.

Furthermore, in March 2007, Siemens and consortium partner Bharat Heavy Electricals Ltd (BHEL) have been awarded an order by the Power Grid Corporation of India Ltd, New Delhi, to construct a new HVDC transmission. The purpose of the new HVDC transmission system is to strengthen the
power supply to the growing region around New Delhi. The system is scheduled to go into service in November 2009. This is the fourth long-distance HVDC transmission link in India.

The power transmission system is to transport electrical energy with low loss from Ballia in the east of Uttar Pradesh province to Bhiwadi, ca. 800 km away in the province of Rajasthan near New Delhi. In comparison with a conventional 400 kV AC transmission line, this HVDC transmission link improves transmission efficiency so that 688,000 tons of CO₂ will be saved.

As head of the consortium, Siemens has overall responsibility for the project, including the design of the HVDC transmission system, and will deliver the bulk of the core components. The company will also undertake the transport functions, construction work, installation and start-up. Partner BHEL is supplying transformers for one of the two converter stations as well as switchgear components. The new long-distance HVDC transmission link is the second system that Siemens is building in India.

6.5. Getting more Power out of the Grid: SVC Siems - Germany

In Figs. 33-34, an innovative FACTS application with SVC in combination with HVDC for transmission enhancement in Germany is shown [8, 14].

It’s a matter of fact that this project is the first high voltage FACTS controller in the German network. The reason for the SVC installation at Siems substation nearby the landing point of the Baltic Cable HVDC were unforeseen right of way restrictions in the neighboring area, where an initially planned new tie-line to the strong 400 kV network for connection of the HVDC was denied. Therefore, with the existing reduced network voltage of 110 kV, only a limited power transfer (450 MW) with the DC link was possible since its commissioning in 1994, in order to avoid repetitive HVDC commutation.
failures and voltage problems in the grid. In an initial step towards grid access improvement, an additional transformer for connecting the 400 kV HVDC AC bus to the 110 kV bus was installed.

Fig. 33: SVC Siems, Germany - Support of HVDC Baltic Cable

Fig. 34: The Solution – the first HV SVC in the German Grid at Siems Substation
Finally, in 2004, with the new SVC, equipped with a fast coordinated control, the HVDC could fully increase its transmission capacity up to the design rating of 600 MW. In addition to this measure, a new cable to the 220 kV grid was installed to increase the system strength with regard to performance improvement of the HVDC controls.

The enhanced grid access of the HVDC can save an amount of 634,000 tons of CO₂ emissions p.a. through the import of more hydro power from Nordel to Germany.

Prior to commissioning, intensive studies were carried out; first with the computer program NETOMAC and then with the RTDS real-time simulator by using the physical SVC controls and simplified models of the HVDC [14].

In Fig. 34, a view of the Siemens SVC in Germany is depicted.

7. CONCLUSIONS

Deregulation and privatization are posing new challenges on high voltage transmission systems. System elements are going to be loaded up to their thermal limits, and wide-area power trading with fast varying load patterns will lead to an increasing congestion.

Environmental constraints, such as energy saving, loss minimization and CO₂ reduction, will play an increasingly important role [1, 10]. The loading of existing power systems will further increase, leading to bottlenecks and reliability problems. As a consequence of “lessons learned” from the large blackouts in 2003, advanced transmission technologies will be essential for the system developments, leading to Smart Grids (see Fig. 35) with better controllability of the power flows.
HVDC and FACTS provide the necessary features to avoid technical problems in the power systems; they increase the transmission capacity and system stability very efficiently, and they assist in prevention of cascading disturbances. They effectively support the grid access of renewable energy resources and reduce the transmission losses by optimization of the power flows.

Bulk power UHV AC and DC transmission will be applied in emerging countries such as India and China to serve their booming energy demands in an efficient way.

8. REFERENCES


[5] FACTS Overview; IEEE and Cigré, Catalog Nr. 95 TP 108


[17] W. Ma: “Main Aspects of UHVDC System Planning and Design”;  
Brazil-China-India Summit Meeting on HVDC and Hybrid Systems – Planning and Engineering Issues, July 16-18, 2006, Rio de Janeiro, Brazil

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