Smart Transmission System by HVDC and FACTS

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Abstract – Nowadays more than ever before, electric power becomes fundamental to modern society’s existence. The power demand for electricity has been growing very fast during the last decades with a high impact on global climate and environmental conditions. The answer is grid access of large amounts of Renewable Energy Sources (RES), e.g. wind and solar technology. This, however, makes the power systems more complex and consequently changes the grid structure: the linear energy chain, consisting of large centralized power plant with excellent control features (“power on demand”), is rapidly becoming a complex power matrix with Dispersed Generation (DG), of which many are installed on medium and even low voltage levels. Such a grid structure must be “Smart”. For this reason the smart transmission system is a big challenge for the necessary system stability and reliability requirements of the Grid Code.

Innovative solutions with HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) with LCC (Line-Commutated Converter) and VSC (Voltage-Sourced Converter) technology play an important role in the smart transmission to enable bulk power long-distance transmissions and grid access of RES, to reduce transmission losses and CO₂ emissions, to interconnect countries and even continents for an open electricity market and to improve the transmission stability. In this paper, the benefits of the HVDC and FACTS technology for transmission system enhancement are discussed and project applications are presented.

Index Terms – HVDC “Classic”, HVDC PLUS, SVC PLUS, Grid Enhancement, RES, DG, Power System Stability

I. INTRODUCTION

The vision and enhancement strategy for the future electricity networks are, for example, depicted in the program for “SmartGrids”, which was developed within the European Technology Platform (ETP). Features of a future Smart Grid like this can be outlined as follows [1]:

- Flexible: fulfilling customer’s needs whilst responding to the changes and challenges ahead
- Accessible: granting 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

Nowadays when discussing about smart grids, the smart distribution system seems to have the highest priority in the grid development; however the other systems – smart generation and smart transmission – have a similar importance in order to efficiently drive the whole grid into a smart power system. When high investments for generation systems are made to supply bulk power to the distribution level, the smart transmission system is essential to avoid bottlenecks and system instabilities. Power electronic controllers HVDC and FACTS offer fast control of active and reactive power, as well as the flexibility to configure the system in a flexible way. Since the commercial application of HVDC after the 2nd World War in 1945 (Germany), 1951 (Russia) and 1954 (Sweden) [2] and FACTS in 1974/1975 (USA) [3], the development of transmission technology has started moving forward in big steps.

The paper will first discuss the challenges in generation, transmission and distribution systems. Then, the benefits of HVDC and FACTS for power system enhancement will be explained. Furthermore, outstanding project applications will be depicted. Finally, the conclusion how HVDC and FACTS can make the whole grid smart will be summed up.

II. CHALLENGE IN GENERATION, TRANSMISSION AND DISTRIBUTION SYSTEMS

In the nearest future we will have to face two mega-trends, as shown in Fig. 1. One is the demographic change. Strong increase in population is foreseen in developing and emerging countries. The other mega-trend is the urbanization with its dramatic growth worldwide. People will mostly live in cities and less in the rural area. These mega-trends drive the demand for a worldwide growing infrastructure [4].

The increase in population and the growing urbanization cause high demand for energy, therefore new kinds of energy sources have to be sought. Unfortunately, natural energy sources are located far away from the load centers and strong environmental constraints become the limitation on conventional power plant expansions. For example in China, the big sources of hydro power are mostly on the western area where the distance from load centers on the eastern areas is above 1,000 km, in some areas even longer than 2,000 km.

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Additionally after the Fukushima event the use of nuclear power plant becomes a concerned issue around the world. To keep the energy security and sustainability for Asia in the 21st century, in Japan the “Asia Super Grid” to share the energy resources of each country in Asia over 36,000 km transmission system is an emerging issue [5]. In Europe the energy policies have been progressively promoting renewable energy sources with maintaining acceptable system reliability standards. Many of the large scale renewable sources like onshore and offshore wind farms have been installed far away from consumption areas. Additionally, the Right-of-Way (ROW) constraints and environmental awareness limit the expansion of the transmission system. Such limitations, together with deregulation and privatization, are posing new challenges on high voltage transmission and distribution systems. With these factors they result in an increase in distributed generation and RES. This can only be solved by a capacity increase in big energy highways with bulk power transmission over long distances via overhead lines and cables. This is also a big challenge to the TSOs (Transmission System Operators) to deal with the rapid and unpredictable load flow changes with the requirement of flexible, efficient and secure grids.

The trend of world electricity power generation, shown in Fig. 2, is expected to grow at 2.8% p.a from 2010 to 2030. The capacity development shifts towards RES while conventional fossil and hydro keeps more than 50% share and an increasing price competition between fossil and renewable power generation. Particularly the new additions of power generation in emerging countries and retirements from developed countries will drive the market. Furthermore the global power plant market grows slower than before the recession but still remains at a high level.

For distribution systems the significant changes in the energy system require a new Smart Grid infrastructure. Smart technologies need to accommodate distributed energy generation and allow consumption management. The consumers drive new applications within the distribution infrastructure e.g. smart metering and PMUs (Phase Measurement Units), smart monitoring systems and novel communication systems [6].

For transmission systems the UHV (Ultra High Voltage) transmission enables long distance power transmission through HVDC and HVAC. In addition, HVDC provides the opportunities to link offshore wind farms where the sources of energy have a distance of more than 80 km in which the reactive power becomes a problem for solutions with AC cables. In some onshore wind farm applications the HVAC cable transmission has shown a big impact of the excessive reactive current drawn by cable capacitance on the Power Quality at the grid connection point. This may require the dynamic shunt stabilization e.g. with SVC (Static Var Compensator) or SVC PLUS® (STATCOM: Static Synchronous Compensator) [7] to control the excessive reactive power demand of the cable which can cause high overvoltages and resonances. In what follows, the enhancement of power system by HVDC and FACTS will be discussed in details.

### III. BENEFITS AND POWER SYSTEM ENHANCEMENTS BY HVDC AND FACTS

Due to a dramatic growth of power demand in densely populated areas, the enormous amounts of power must be transmitted to large load centers with overhead lines and cables. The higher voltage levels are required to optimize the transmission losses. Using power electronic devices – HVDC and FACTS – provides the necessary control features to enhance the power system.

In HVAC applications the power transmission capability is limited by the load dependent phase shift along the transmission line, the voltage drop of the line and the thermal limits of its conductors. In long overhead lines a key factor to limit the power transfer is the SIL (Surge Impedance Loading). During normal operations the transmission line can transmit a certain amount of active and reactive power without exceeding a specified voltage tolerance band, typically ±5%. When the load is equal to the SIL, the line voltage remains constant along the whole length of the line. To give an example: a typical 400 kV AC line has a SIL of maximal 700
MVA. However, in meshed systems with short lines, the lines are typically loaded up to two times of SIL or even higher. The extreme value is given by the thermal limiting factor, typically three times of SIL. High load at the end of the line requires dynamic shunt compensation, such as SVC or SVC PLUS to control the voltage within specified values according to the Grid Code. HVDC applications mostly use also voltage control functions for reactive power compensation at the grid connection point. Furthermore, HVDC can transmit bigger power at lower losses in the same transmission corridor compared with an AC transmission at the same voltage. Fig. 3 shows a comparison of AC and DC transmission at different voltage levels. For comparison, cable parameters are also given.

With lower losses in the HVDC transmission, typically 30-50% at the same voltage and power, it is efficient to connect remote power plants over long distances and CO₂ emissions are consequently reduced. Additionally, the fully controllable power flow of the HVDC can improve the stability of large synchronous and asynchronous interconnected systems. During the big blackout in 2003 in the USA and Canada, the HVDCs in Québec apparently have impressively proven their firewall function against cascading disturbances and acted as a barrier for stability problems and a voltage collapse. This protected the Quebec region from the upcoming blackout, while Ontario, which had no DC at its border to the USA, was fully affected and joined the large disturbance. In addition, the DCs of Québec supported the US network during the system restoration after the blackout. One major advantage of using power electronic devices is the fast control feature which is necessary for system stability. Fig. 4 shows the benefit of a hybrid system interconnection when the fault occurs on an AC line. It can be seen that with the functionality of HVDC, the power oscillations are quickly damped and the interconnection gets back to the pre-fault condition quite fast. Without the DC damping function, the oscillations are increasing and the interconnection must be tripped.

In terms of environmental and social concerns the ROW of HVDCs is narrower comparing with HVAC systems. Fig. 5 depicts the comparison of AC and DC towers at the same power transfer. Obviously, with the DC link it is the more environmental friendly solution. Regarding redundancy, one bipolar DC system is equivalent to a double-circuit AC system, with much bigger ROW requirement.

**DC versus AC – Overhead Line and Cable Data**

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**Table 3. Loss Comparison between DC and AC Systems**

**Fig. 3. Loss Comparison between DC and AC Systems**

**Fig. 5. Comparison of Towers 800 kV AC and 500 kV DC**

**FACTS technology encompasses systems for both parallel and series compensation.** The general problems in power systems which can be solved by FACTS are congestion of transmission lines, inter-area and local power oscillations, flicker, voltage unbalances and voltage variations at different load conditions, reactive power balancing, high short-circuit currents and voltage as well as phase-angle in stability. The most common application of series compensation is FSC (Fixed Series Capacitor), TCSC (Thyristor Controlled Series Capacitor), TPSC (Thyristor Protected Series Capacitor) and FSR (Fixed Series Reactor). For parallel compensation, MSC (Mechanically Switched Capacitor), MSR (Mechanically Switched Reactor), MCDN (Mechanically Switched Capacitor with Damping Network), SVC and SVC PLUS are frequently used.

Power electronics is used in high-voltage systems for FACTS in a similar way as for HVDC. This provides the possibility of FACTS to improve the system performance during and after disturbances. Fig. 6 shows the application of series compensation consisting of FSCs and TCSCs. It can be seen that with the control functions of TCSC the system can be stabilized quite well.
Fig. 6. Efficient Power Oscillation Damping of a long Transmission System by TCSC

Fig. 7 depicts an example of parallel compensation with SVC for power oscillation damping after a fault application on a 1,000 km long 500 kV AC double line (permanent 3-ph fault without auto-reclosure). With two SVCs, connected in the middle of the line, the system stability is increased and consequently more power can be transmitted.

The previous study cases and applications demonstrate the importance of HVDC and FACTS for power system enhancement towards a more stable and Smart Grid. In the next section, outstanding technology innovations in projects with HVDC and FACTS are discussed.

IV. EXAMPLE OF HVDC AND FACTS SOLUTIONS

In 2010, Siemens was awarded one large order of three SVC projects from the Saudi Electricity Company (SEC). In this region the demand for electricity has continuously increased. Comparing the year 2011 with 2010, the growth of the available generation capacities, the transmission network length and the distribution length has been increased by 4.1%, 7.6% and 7.3%, respectively [8]. Purposes of the new SVCs in the system are to provide adequate reactive power support, to limit over-voltages and to prevent voltage collapse or motor stalling phenomena during single-phase to ground faults. The SVCs are deployed at three sites in Hiteen, Qassim and Afif in the central region as shown in Fig. 8. The SVC Hiteen is located directly in Riyadh, the capital of Saudi Arabia. The SVC Qassim is placed in the province of Qassim, close to the city of Buraidah, 400 km northwest of Riyadh. The SVC Afif is located in the city of Afif, 450 km west of Riyadh, half-way between Riyadh and Mecca.

The SVCs Hiteen, Qassim and Afif are installed at different high voltage levels of 380 kV, 132 kV and 33 kV and have dynamic compensation capacities of 200 ind. to 800 cap. Mvar, 150 ind. to 450 cap. Mvar and 50 ind. to 100 cap. Mvar, respectively. The Afif SVC was already put in operation in the last quarter of 2011 and the Hiteen and Qassim SVCs have been fully operated in the third quarter of 2012. The dynamic performance test of these three SVCs on Real-Time Digital Simulator (RTDS) with a large implemented network confirms that these SVCs can efficiently supply reactive power during faults and can consequently prevent motor stalling phenomena resulting in voltage collapse [9].

In the UK, the Western HVDC Link, shown in Fig. 9, with a new DC submarine cable link is currently installed to increase the power exchange and to bypass the congested onshore overhead lines. The project owners are National Grid and Scottish power. The power rating is 2,200 MW with the World’s first 600 kV DC MI cable (Mass-Impregnated). The cable length is 420 km. To strengthen the Northern Grid Access of the HVDC, two SVC PLUS of 2x125 Mvar will be installed to dynamically control voltage and reactive power at the Scottish network.
In Queensland, Australia, three new SVC PLUS systems are installed at the Wycarbah, Duaringa and Bluff substation, as shown in Fig. 10. The capacity of each SVC PLUS is ±100 Mvar. There is a substantial increase in the volume of coal exported from Central Queensland expected in the near future. As the system is relatively weak, Static Var Compensators (SVCs) were installed coincidently with the introduction of electric locomotives during the late 1970s, to maintain quality of supply for other customers in the region. However, the existing SVCs cannot cope with the predicted increase of the Queensland Railways load. This increase will affect the power quality and increase the unbalance in the region [10]. Installation of these three SVC PLUS can efficiently solve the problem.

In the European transmission grid the implementation of HVDCs shown in Fig. 11 is growing step by step. The HVDC interconnections used in the past mostly LCC and now increasingly more the VSC technology. Such an outstanding HVDC project in Europe which is designed for efficient, flexible and controllable power supply by using the latest Multilevel VSC technology is shown in the next section.

The first European HVDC VSC type onshore interconnection and the world’s biggest converter stations using the latest technology - HVDC PLUS - named INELFE (Interconnection Electrique France-Espagne, or France-Spain electrical interconnection) is shown in Fig. 12. This HVDC link is fully integrated into the synchronous AC system and supports the interconnection of Spain and France. The project is supported by the European Energy Program for Recovery (EEPR). Currently, Spain and France are only interconnected by four AC transmission cross-border lines, two 400 kV lines and two 220 kV lines. These lines have a high importance for linking the Iberian Peninsula (Spain and Portugal) to the rest of the European grid. Now the need for increasing the transfer capacity has got a high importance for both systems. Drivers are the liberalization of the electricity market, the requirements of the European Union about a European Market in the 90s and more recently the strategy 20-20-20. The INELFE project has therefore a high priority in the European network developments [11]. The HVDC PLUS solution with two parallel systems and four 65 km long XLPE DC cables with a DC voltage of ±320 kV will interconnect the 400 kV AC grid of RTE (Réseau de Transport d'Electricité) in France and the 400 kV AC grid of REE (Red Eléctrica de España) in Spain. The power rating will be 2,000 MW transmission capability. The converter stations are able of controlling reactive power in a range of 600 Mvar capacitive power to 600 Mvar inductive power independently from active power.
V. CONCLUSIONS

In this paper it has been shown that there are two megatrends - demographic change and urbanization – which are causing a high demand of electrical energy. The development of power grids consisting of generation, transmission and distribution is therefore a big challenge, today and in the future. Global investments for generation are expected within 2010 to 2030 with an increase of 2.8% every year. To transmit the generated power to the load centers efficiently a smart transmission system will be needed. Innovative solutions with HVDC and FACTS have the potential to cope with the new challenges. By means of Power Electronics, they provide features which are necessary to avoid technical problems in the power systems; they increase the transmission capacity and system stability very efficiently and help prevent cascading disturbances. So, HVDC and FACTS will play an important role in the Smart Grid developments.

Regarding long distance Bulk Power transmission, HVDC is the best solution, offering minimal losses. It goes without saying that a combination of FACTS and classic line-commutated HVDC technology is feasible as well. In the case of state-of-the-art VSC-based HVDC technologies e.g. HVDC PLUS, the FACTS function of reactive power control is already integrated, additional FACTS controllers are superfluous. However, “Bulk Power” transmission up to a range of eight GW (at present) remains reserved to classic, line-commutated thyristor-based HVDC systems.

VI. REFERENCES


VII. BIOGRAPHIES

Pakorn Thepparat was born in Thailand in 1978. He received the B.Eng. degree at the Kasetsart University, Thailand in 2001, the M.Sc. degree at the RWTH Aachen, Germany in 2006 and the Dr.-Ing. at the Ilmenau University of Technology, Germany in 2010. All degrees are in Electrical Engineering.

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Dietmar Retzmann was born in Pfalzfeld, Germany on November 4, 1947. He graduated in Electrical Engineering (Dipl.-Ing.) at the Technische Hochschule Darmstadt, Germany in 1974 and received the Dr.-Ing. Degree from the University of Erlangen-Nürnberg in 1983.

Dr. Retzmann is with Siemens Erlangen in Germany since 1982. He is director of Technical Marketing & Innovations HVDC/FACTS in the Energy Sector, Power Transmission Solutions. His area of expertise covers project development, simulation and testing of HVDC, FACTS, System Protection and Custom Power as well as system studies, innovations and R&D activities.

Dr. Retzmann is active in IEEE, Cigré, ZVEI and VDE. He is author and co-author of over 220 technical publications in international journals and conferences. In 1998, he was appointed guest-professor at the Tsinghua University, Beijing, and in 2002 at the Zhejiang University, Hangzhou, China. Since 2004, he is lecturer on Power Electronics at the University of Karlsruhe, Germany and in 2011 he becomes lecturer on Power Electronics and Electrical Energy Systems at the University of Erlangen-Nürnberg, Germany. In 2006, he was nominated "Siemens TOP Innovator".

Emmanuel Ogée was born in Suresnes-sur-Seine, France, on November 9, 1970. He graduated in Instrumentation (Dipl.-Ing) at the Polytech'Lille Engineering School, Lille, France in 1994 and received an executive MBA from Edhec Business School, Lille, France in 2008.

He joined Siemens Energy France in 2007 as Sales Engineer and was in charge of High Voltage projects and notably the Inelfe project. Since 2011, he is Sales Manager HVDC in the Marketing & Sales department of Siemens AG in Erlangen, Germany. He is responsible for HVDC projects (mostly VSC based) in Europe.

Markus Wiesinger was born in Austria, 1970. He completed his technical education in electrical engineering in Linz, Austria 1996. He joined Trench in 1996 and worked as marketing and sales manager for air core reactors. Since 2008 he works for Siemens Energy Sector, Power Transmission Solutions as a sales manager for FACTS projects.