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Survey Paper

Integrated AC/DC Transmission Systems – Benefits of Power Electronics for Security and Sustainability of Power Supply

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Extended Summary

Deregulation and privatization is posing new challenges on high voltage transmission and on distributions systems as well. An increasingly liberalized market will encourage trading opportunities to be identified and developed. Environmental constraints, such as energy saving, loss minimization and CO₂ reduction, will also play an important role. The loading of existing power systems will further increase, leading to bottlenecks and reliability problems. Consequently, we have to deal with an area of conflicts between reliability of supply, environmental sustainability as well as economic efficiency.

High voltage power electronics, such as HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) provide the necessary features to avoid technical problems in heavily loaded power systems; they increase the transmission capacity and system stability very efficiently, and they assist in prevention of cascading disturbances. Furthermore, they effectively support the grid access of renewable energy resources and they reduce the transmission losses by optimization of the power flows.

HVDC offers most advantages: it can be used for system interconnection and for control of power flow as well. The major benefit of HVDC is its incorporated ability for fault-current blocking, which is not possible with synchronous AC links. In addition, HVDC can effectively support the surrounding AC systems in case of transient fault conditions and it serves as firewall against cascading disturbances.

FACTS, based on power electronics, have been developed to improve the performance of weak AC Systems and for long distance AC transmission. FACTS controllers can, however, also contribute to solve technical problems in the interconnected power systems. FACTS are applicable in parallel connection, in series connection, or in combination of both to control load flow and to improve dynamic conditions. By these means, FACTS contributes to Blackout prevention too. Therefore, the strategies for the development of large power systems go clearly in the direction of hybrid transmissions, consisting of DC and AC interconnections and point-to-point bulk power transmission “highways” (AC and DC Backbones), including FACTS.

Fig. 1 shows the stepwise interconnection of a number of grids, using AC lines, DC Back-to-Back systems, DC long distance transmissions and also FACTS for strengthening the AC lines. Such hybrid systems offer significant advantages, both technical and economical as well as in terms of system security. They offer lower transmission costs as well as the possibility of bypassing heavily loaded AC systems. This approach is an important step in the direction of environmental sustainability of power supply: transmission technologies with HVDC and FACTS can effectively contribute to reduction in transmission losses and CO₂ production. Fig. 2 depicts the idea of a bulk power DC backbone in Western Europe, which will enable the integration of large amounts of regenerative energy sources, such as hydro and solar plants as well as offshore wind farms.

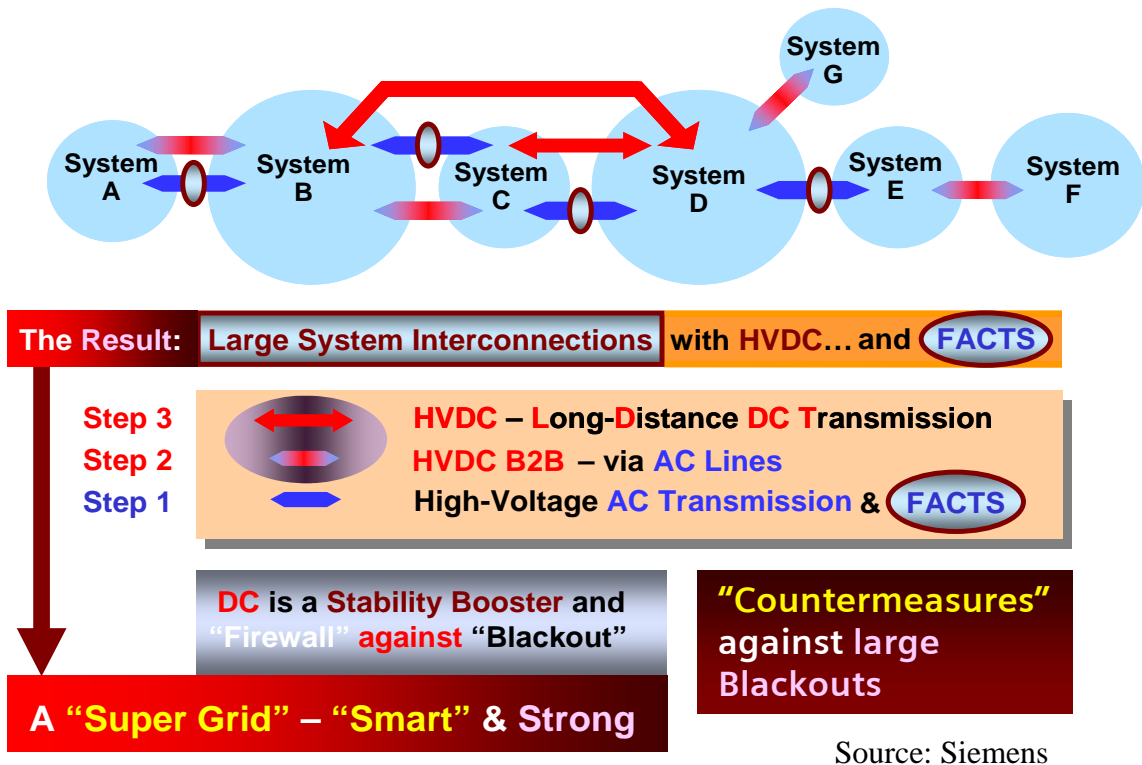


Fig. 1: Hybrid System Interconnections – "Supergrid" with HVDC and FACTS

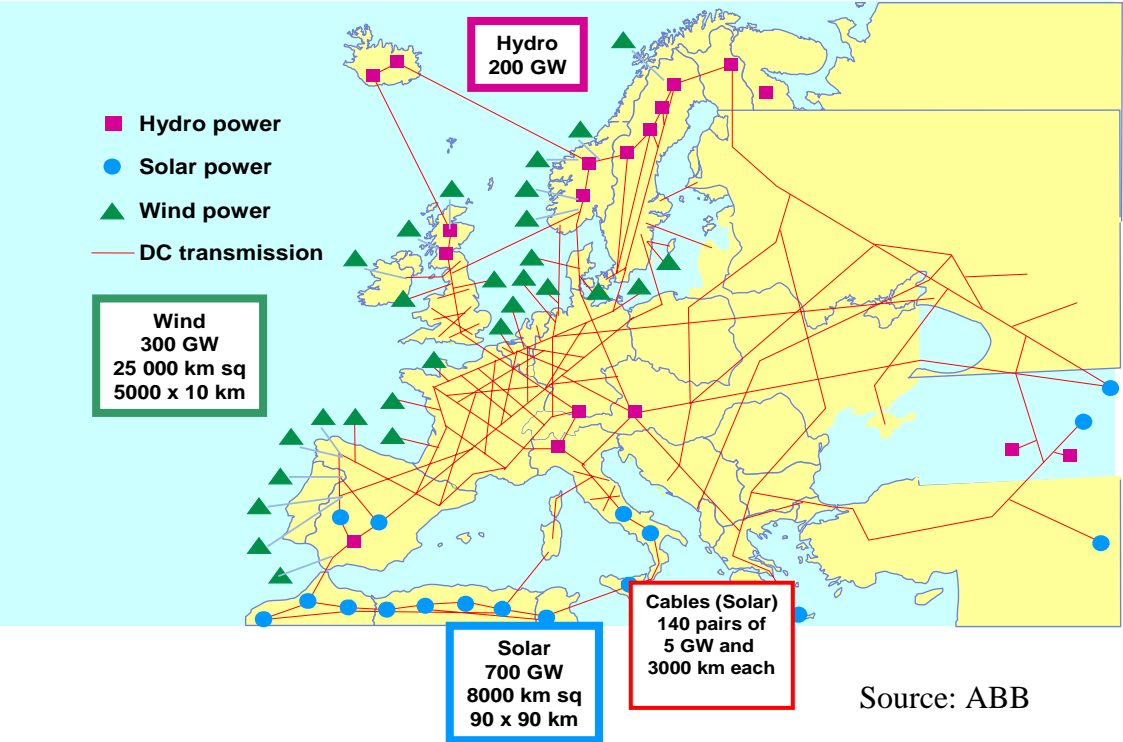


Fig. 2: DC Backbone in Europe for Integration of large Regenerative Energy Sources

In the survey paper, which will be distributed on-site, as well as in the session, examples of projects with HVDC and FACTS in different countries will be presented and their benefits for security and sustainability of power supply depicted.

SURVEY PAPER 2 - PART 1

INTEGRATED AC/DC TRANSMISSION SYSTEMS –

Benefits of Power Electronics for Security and Sustainability of Power Supply

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Abstract – Deregulation and privatization are posing new challenges to high-voltage transmission systems. Environmental constraints, such as energy saving, loss minimization and CO₂ reduction, will also play an increasingly more important role. The loading of existing power systems will further increase which will lead to bottlenecks and reliability problems. High-voltage power electronics, such as HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems), provide the necessary features to avoid technical problems in heavily loaded power systems; they increase the transmission capacity and system stability very efficiently and assist in preventing cascading disturbances. Therefore, the strategies for the development of large power systems go clearly in the direction of hybrid transmissions, consisting of integrated AC/DC interconnections and point-to-point bulk power transmission “highways” (AC and DC Backbones). FACTS technology is also an important part of this strategy. These hybrid systems offer significant advantages in terms of technology, economics and system security. They reduce transmission costs as well as help bypass heavily loaded AC systems.

Keywords: Security and Sustainability of Power Supply; Elimination of Bottlenecks in Transmission; Blackout Prevention; Increase in Transmission Capacity; HVDC and FACTS Technologies

1 INTRODUCTION

The electric power supply is essential for the survival of a society, like the blood in the body. Lack of power brings about devastating consequences for daily life. However, deregulation and privatization are posing new challenges to the 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 contribute to an increasing congestion.

In addition to this, the dramatic global climate developments call for changes in the way electricity is supplied. Environmental constraints, such as loss minimization and CO₂ reduction, will play an

increasingly important role. Consequently, we have to deal with an area of conflicts between reliability of supply, environmental sustainability as well as economic efficiency [3, 4]. The power grid of the future must be secure, cost-effective and environmentally compatible [2]. The combination of these three tasks can be tackled with the help of ideas, intelligent solutions as well as innovative technologies.

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.

2 HVDC AND FACTS TECHNOLOGIES

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 less than a 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 and further projects with 6 - 7 GW or even higher are at the planning stage.

In general, for transmission distances above 600 km, DC transmission is more economical than AC transmission (≥ 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 approx. 1,000 km are at the planning stage. Due to these developments, HVDC became a mature and reliable technology.

During the development of HVDC, different kinds of applications were carried out. They are shown schematically in Fig. 1. The first commercial applications were cable transmissions, for 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 [5]. 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. 1a). A further application of HVDC transmission which is highly important for the future is its integration into the complex interconnected AC system (Fig. 1c). The reasons for these hybrid solutions are basically lower transmission costs as well as the possibility of bypassing heavily loaded AC systems.

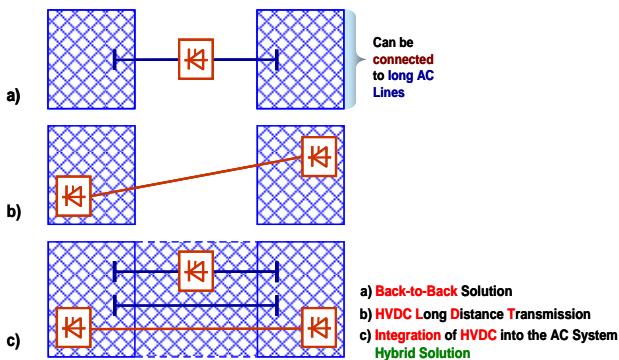


Fig. 1: Options of HVDC Interconnections

Typical configurations of HVDC are depicted in Fig. 2. HVDC VSC is the preferred technology for interconnecting islanded grids, such as offshore wind farms, to the power system [1]. This technology provides the “Black-Start” feature by means of self-commutated voltage-sourced converters [8]. Voltage-sourced converters do not need any “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 VSC with low switching frequencies, referred to as HVDC PLUS [14-16].

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 [10-13], ref. to Fig. 3

HVDC – High-Voltage DC Transmission: It makes P flow

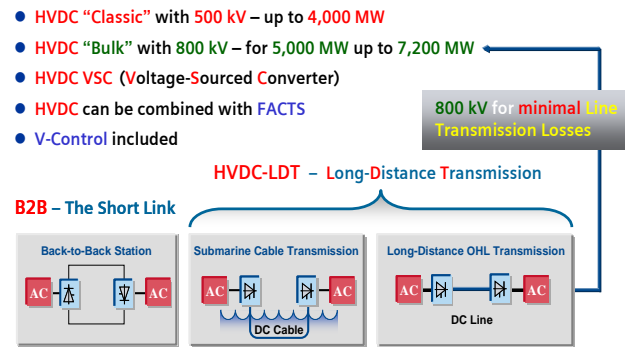


Fig. 2: HVDC Configurations and Technologies

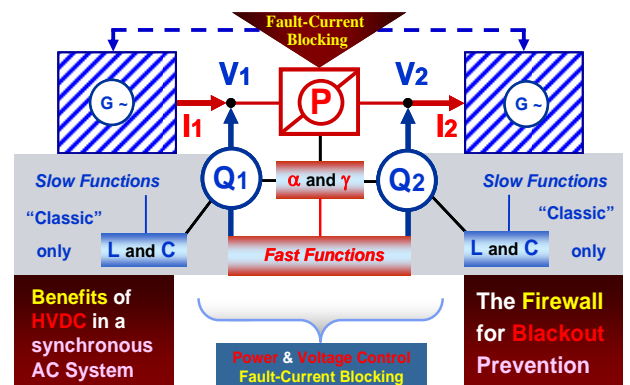


Fig. 3: Benefits of HVDC - it makes Power flow

Since the 1960s, Flexible AC Transmission Systems have been evolving to a mature technology with high power ratings [6, 7, 9]. The technology, proven in various applications, became first-rate, highly reliable one. FACTS, based on power electronics, have been developed to improve the performance of weak AC Systems and to make long distance AC transmission feasible. FACTS can also help solve technical problems in the interconnected power systems. FACTS are available 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 as a combination of both (UPFC, Unified Power Flow Controller - CSC, Convertible Static Compensator) to control load flow and to improve dynamic conditions.

Fig. 4 shows the basic configurations of FACTS. In Fig. 5, the impact of series compensation on Power transmission and system stability is explained and Fig. 6 depicts the increase in voltage quality by means of shunt compensation with SVC (or STATCOM).

FACTS – Flexible AC Transmission Systems: Support of Power Flow

- SVC – Static Var Compensator (The Standard of Shunt Compensation)
- STATCOM – Static Synchr. Compensator, with VSC
- FSC – Fixed Series Compensation
- TCSC – Thyristor Controlled Series Compensation
- TPSC – Thyristor Protected Series Compensation
- UPFC – Unified Power Flow Controller (with VSC)

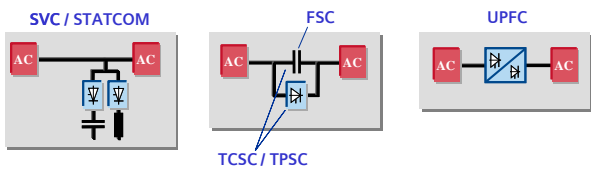


Fig. 4: Transmission Solutions with FACTS

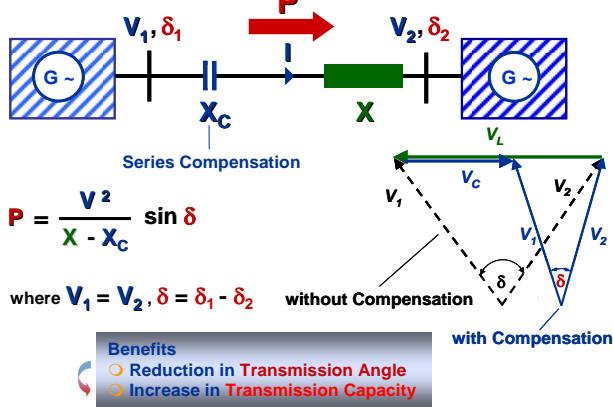


Fig. 5: FACTS - Influence of Series Compensation on Power Transmission

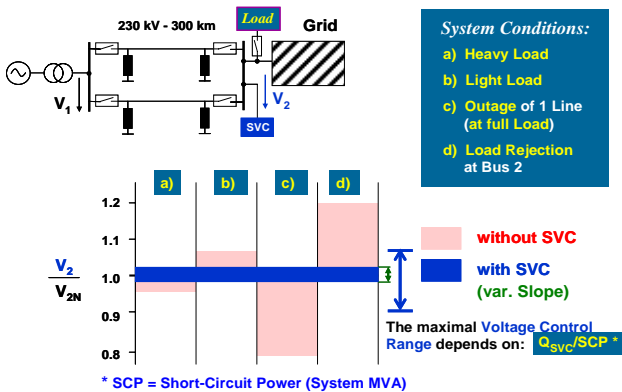


Fig. 6: FACTS - Improvement in Voltage Profile with SVC

3 SECURITY AND SUSTAINABILITY OF POWER SUPPLY WITH INTEGRATED AC/DC TRANSMISSION PROJECTS

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. The task given by Neptune Regional Transmission System LLC (RTS) in Fairfield, Connecticut, was 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, the seamless coverage of the customer's needs was provided. The availability of this combined expertise fulfills the prerequisites for financing these kinds of complex supply projects through the free investment market.

The contractor 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, substantial support was given to the customer during the project's approval process.

In Fig. 7, highlights of this innovative project typical of the future integration of HVDC into a complex synchronous AC system are depicted.

Ed Stern, President of Neptune RTS: "High-Voltage Direct-Current Transmission will play an increasingly important Role, especially as it becomes necessary to tap Energy Reserves whose Sources are far away from the Point of Consumption"

Safe and reliable Power Supply for the Mega Cities - "Blackout Prevention"

Customer:	Neptune RTS
End User:	Long Island Power Authority (LIPA)
Location:	New Jersey: Sayreville Long Island: Duffy Avenue
Project Development:	NTP-Date: 07/2005 PAC: 07/2007
Supplier:	Consortium Siemens / Prysman
Transmission:	Sea Cable
Power Rating:	600/660 MW monopolar
Transmission Dist.:	82 km DC Sea Cable 23 km Land Cable

Fig. 7: Highlights of Neptune HVDC Project - USA

During trial operation, 2 weeks ahead of schedule, Neptune HVDC proved its Blackout prevention capability in a very impressive way. On June 27th, 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 a 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.

Fig. 8 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. 8: 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 from the grid of Victoria during dry seasons when water 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 by the combined use of regenerative energies.

The HVDC East-South interconnection in India (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. A view of the HVDC northern terminal in the state of Orissa is given in Fig. 9.



Fig. 9: Site View of Indian East-South Interconnector – DC Station Talcher

In April 2006, Powergrid Corporation of India decided 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 experts have developed a solution known as Relative Aging Indication and Load Factor Limitation (RAI & LFL). With their help it is possible to utilize the overload capacity of the system more effectively without having to install additional thyristors.

Furthermore, in March 2007, the HVDC manufacturer and his consortium partner Bharat Heavy Electricals Ltd (BHEL) have been awarded an order by 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, approx. 800 km away in the province of Rajasthan near New Delhi. In comparison with a conventional double-circuit 400 kV AC transmission line, this HVDC transmission link improves transmission efficiency so that 688,000 tons of CO₂ will be saved, ref. to Fig. 10.

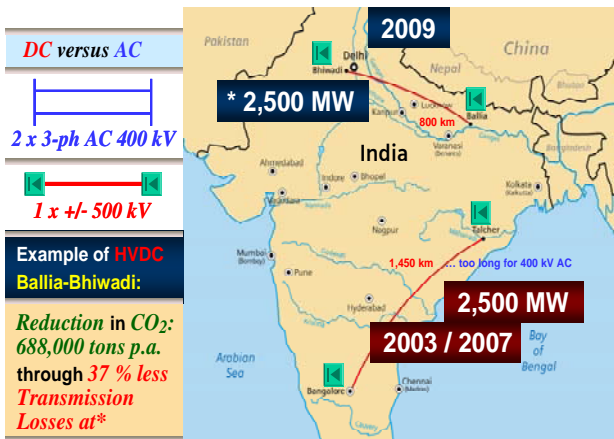


Fig. 10: Sustainability of Transmission in India - East-South Interconnector and Ballia-Bhiwadi

As the head of the consortium, the manufacturer has overall responsibility for the project, including the design of the HVDC transmission system, and will deliver the main core components. The company will also take over 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 built by Siemens in India.

In China, the 3000 MW +/-500 kV bipolar Gui-Guang HVDC system (Fig. 11) with a transmission distance of 980 km was built to increase the transmission capacity from west to east. 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 an AC transmission in this grid.

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.

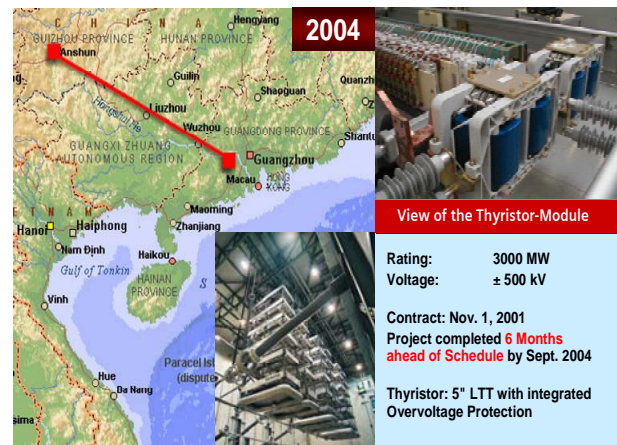


Fig. 11: Highlights of the Gui-Guang HVDC Transmission Project

In June 2007, China Southern Power Grid Company, Guangzhou, placed the order 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 with a power transmission capacity of 5,000 MW. Fig. 12 gives an overview of this project in China Southern Power Grid.

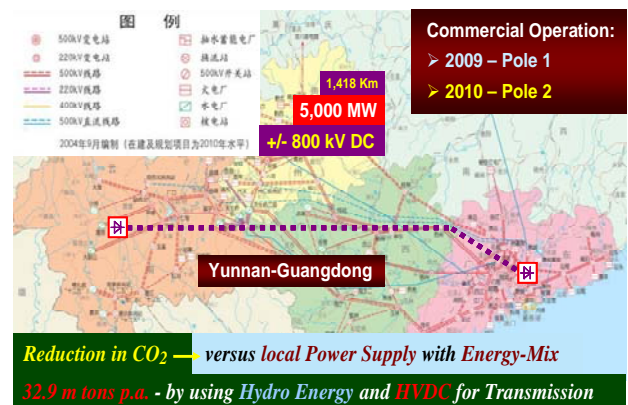


Fig. 12: World's first 800 kV UHV DC – in China Southern Power Grid

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 due to the construction of additional conventional fossil power plants in the province of Guangdong to serve the regional grid.

In Figs. 13-14, an innovative FACTS application with SVC in combination with HVDC for transmission enhancement in Germany is shown.

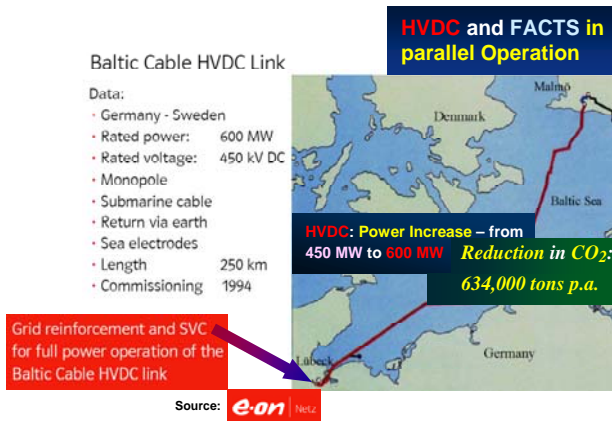


Fig. 13: SVC Siems, Germany - Support of HVDC Baltic Cable

This project is the first high voltage FACTS controller in the German network. The reason for the SVC installation at Siems substation near 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 an 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.

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 power increase of the HVDC system.

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. In Fig. 14, a view of the Siems SVC in Germany is depicted.



Fig. 14: The Solution – the first HV SVC in the German Grid at Siems Substation

In September 2007, two converter stations for a new submarine high-voltage direct-current (HVDC) transmission link in the Bay of San Francisco were ordered. The HVDC PLUS system will transmit up to 400 megawatts at a DC voltage of +/- 200 kV and it is the first order for the innovative HVDC PLUS technology, ref. to Fig. 15.

From March, 2010, the 55 mile (88 kilometers) long HVDC PLUS system will transmit electric power from the converter station in Pittsburg to the converter station in San Francisco, providing a dedicated connection between the East Bay and San Francisco. Main advantages of the new HVDC PLUS link are the increased network security and reliability due to grid enhancement including voltage support and reduced system losses.

Today, the major electric supply for the City of San Francisco is coming from the south side of the San Francisco peninsula. The city relies mainly on AC grids which run along the lower part of the bay – with the new HVDC PLUS interconnection link, power flows directly into the center of San Francisco and closes the loop of the already existing “Greater Bay Area” transmission.

This will increase the system security. Furthermore, the DC cables will be buried in a safe corridor separate from any existing AC cables.

Furthermore, the DC project will save the trouble of building additional new power plants in the City of San Francisco, decrease transmission grid congestion in the East Bay and it will also boost the overall security and reliability of the power system. The order was placed by Trans Bay Cable LLC, based in San Francisco, and a wholly-owned subsidiary of the project developer Babcock & Brown.

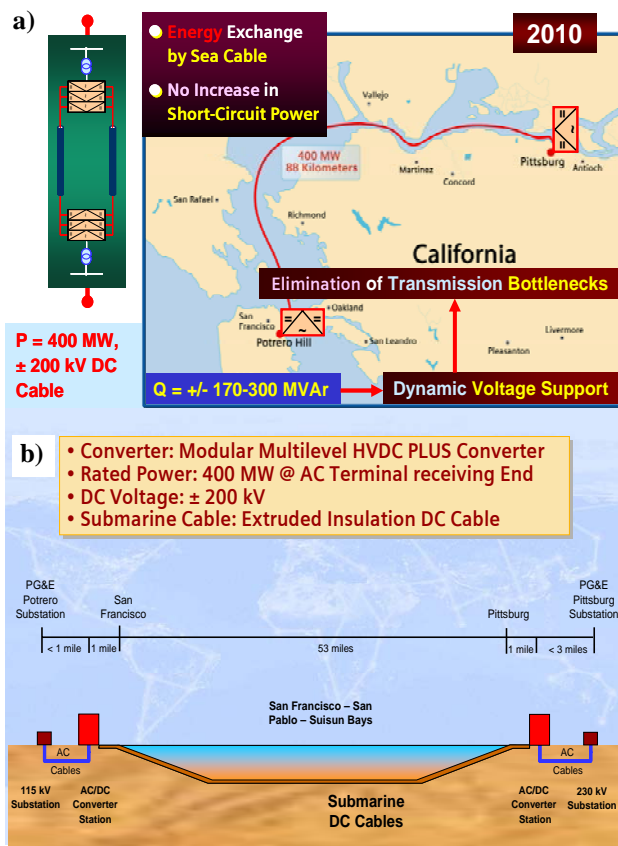


Fig. 15: Trans Bay Cable, USA – World's 1st VSC HVDC Project with Advanced MMC-Technology and +/- 200 kV XLPE DC Cable
a) Geographic Map and System Requirements
b) Siemens Converter Stations and Prysmian Cable Technologies

As the consortium leader, the HVDC manufacturer was awarded a turnkey contract which comprises the converter stations for the HVDC PLUS system, including engineering, design, manufacturing, installation and commissioning of the HVDC transmission system. All high voltage components including transformers, converter modules, converter reactors and breakers will be delivered. The contractor will also be responsible for the control and protection system, civil works as well as building technologies. Furthermore, all major requirements are to be fulfilled, which have to be considered for the electrical components as well as for all buildings for a highly seismic zone such as San Francisco. The HVDC PLUS solution can meet all the requirements in terms of the minimum space available for the converter sites in urban areas as well as in terms of the less significant environmental impact such as visual implication, audible noise and transport during construction. The consortium partner Prysmian will supply and install the submarine cables.

The new VSC technology for HVDC PLUS with Modular Multilevel Converter (MMC) provides tremendous benefits for power transmission. It is fully suited for integrated AC/DC system application and it will help increase sustainability and security of transmission systems significantly. As an example, a palpable reduction in transmission constraints by using HVDC PLUS for the Trans Bay Cable Project is depicted in Fig. 16.

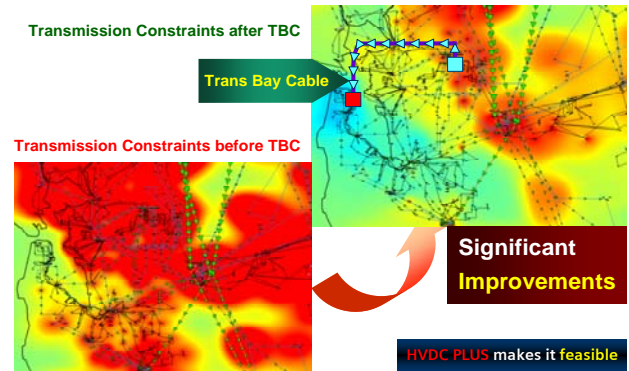


Fig. 16: Benefits of HVDC PLUS for Trans Bay Cable Project

4 SIMULATIONS AND STUDIES FOR HVDC AND FACTS

Figs. 17-18 give an example of a large power system simulation of the Chinese grid, in which both FACTS and HVDC have been integrated for grid interconnection and point-to-point long distance transmission in a hybrid way.

Because of the long transmission distances, the system experiences severe power oscillations after faults, close to the stability limits. In the recordings in Fig. 18 oscillations are depicted (upper part). The first case given is HVDC transmitting power in constant power mode, see curve a. It can be seen that strong power oscillations occur. If, however, damping control of HVDC Gui-Guang is activated (curve b), the oscillations are damped very effectively. Using series compensation with two TCSCs and two FSCs at Pingguo substation, the stability of the overall system can be further increased (curve c). The lower part of Fig. 18 shows that without HVDC POD, the Pingguo TCSCs need more actions for damping: 1a) compared to 2a)-b). Without series compensation and without HVDC damping, a power system as large as this one would be unstable in case of fault contingencies, consequently leading to severe outages (Blackout). Stability studies have been carried out with the computer program PSSTMNETOMAC, followed by intensive digital Real-Time Simulator tests with RTDSTM.

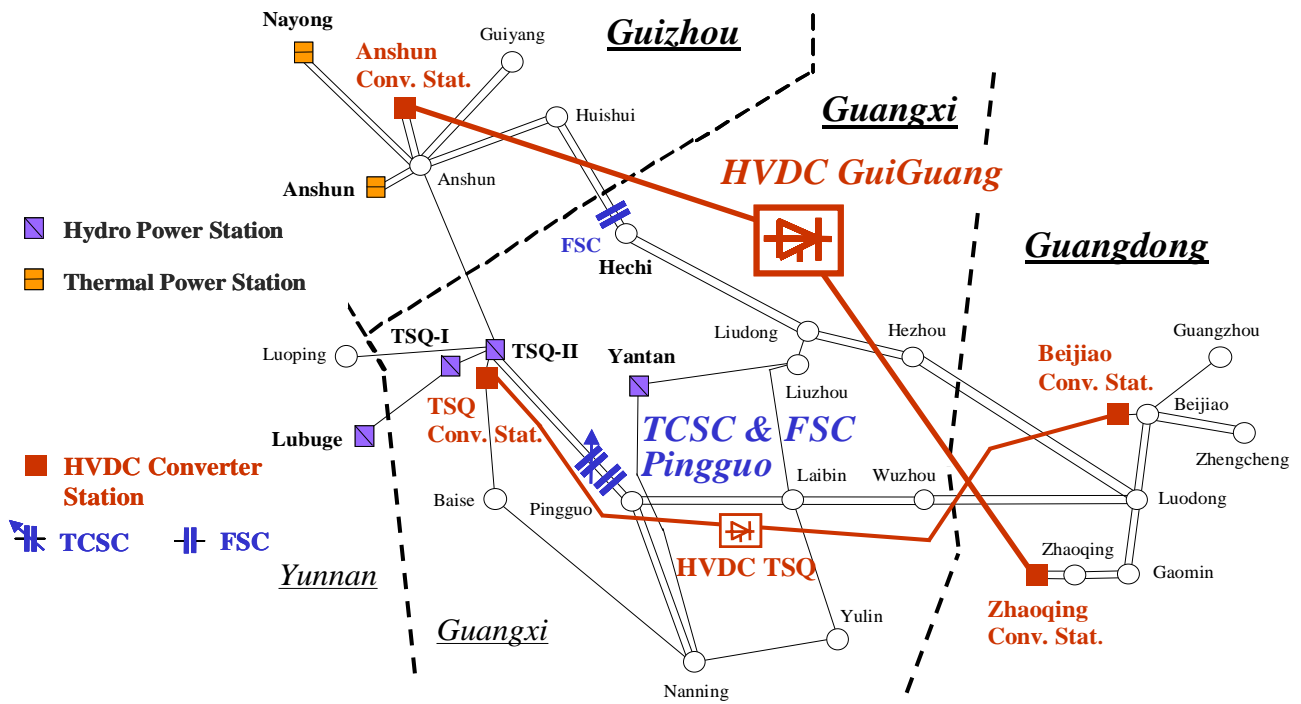


Fig. 17: Integrated AC/DC Transmission - Use of HVDC and FACTS in a hybrid System in China

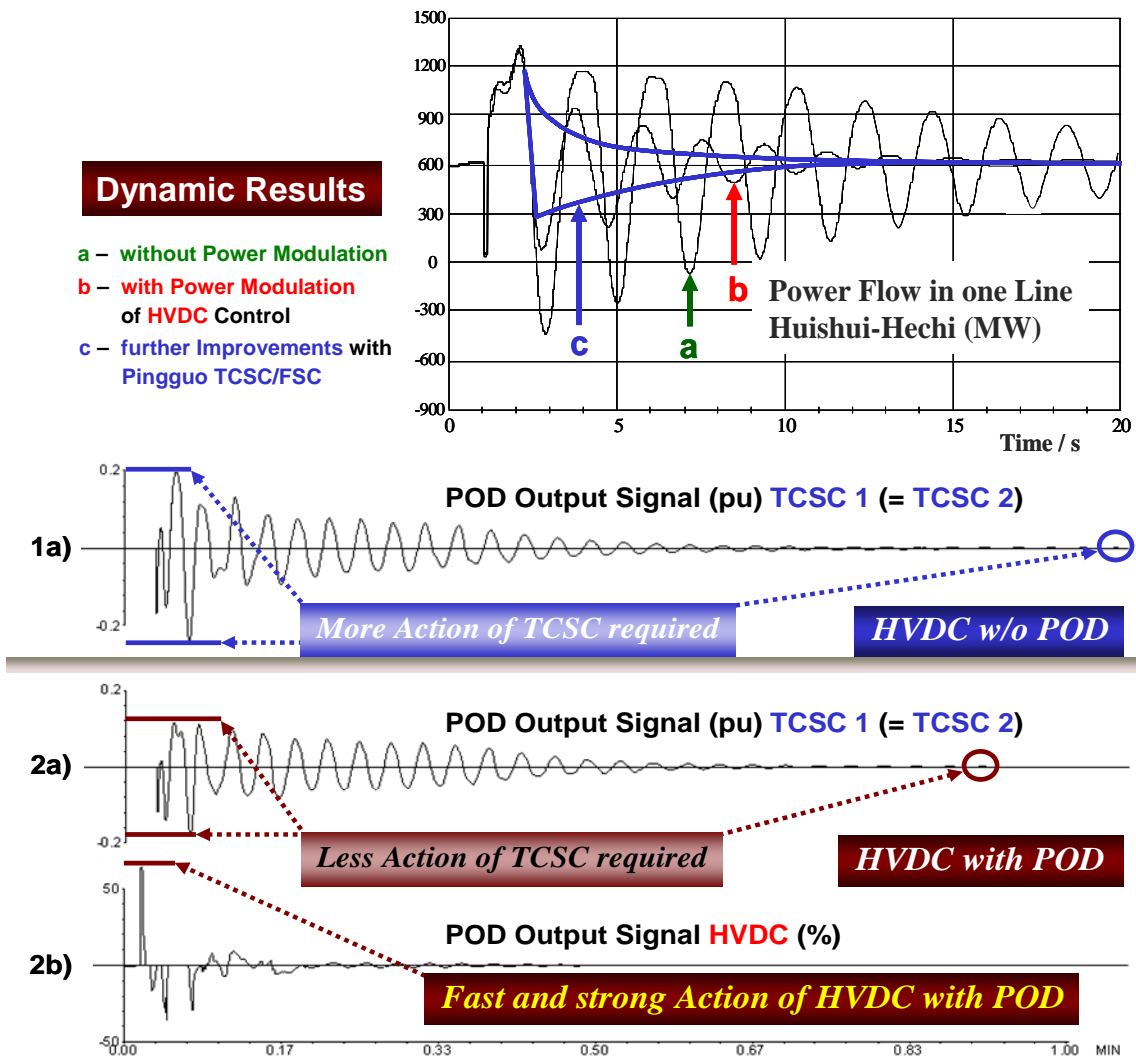


Fig. 18: China - Benefits of active Damping with HVDC & FACTS (ref. to Text)

5 CONCLUSIONS

In conclusion to the previous sections, Table 1 summarizes the impact of FACTS and HVDC on load flow, stability and voltage quality when using

different devices. Evaluation is based on a large number of studies and experiences from projects. For comparison, mechanically switched devices (MSC/R) are included in the table.

Principle	Devices	Scheme	Impact on System Performance		
			Load Flow	Stability	Voltage Quality
Variation of the Line Impedance: Series Compensation	FSC (Fixed Series Compensation)		●	● ● ●	●
	TPSC (Thyristor Protected Series Compensation)		●	● ● ●	●
	TCSC (Thyristor Controlled Series Compensation)		● ●	● ● ●	●
Voltage Control: Shunt Compensation	MSC/R (Mechanically Switched Capacitor / Reactor)		○	●	● ●
	SVC (Static Var Compensator)		○	● ● ●	● ● ●
	STATCOM** (Static Synchronous Compensator)		○	● ● ●	● ● ●
Load-Flow Control	HVDC – B2B, LDT HVDC PLUS – VSC		● ● ● ●	● ● ● ●	● ● ● ●
	UPFC (Unified Power Flow Controller)		● ●	● ● ● ●	● ● ● ●

Influence: *

- no or low
- small
- ● medium
- ● ● strong

* Based on Studies & practical Experience

** = SVC PLUS

Table 1: FACTS & HVDC – Overview of Functions & “Ranking”

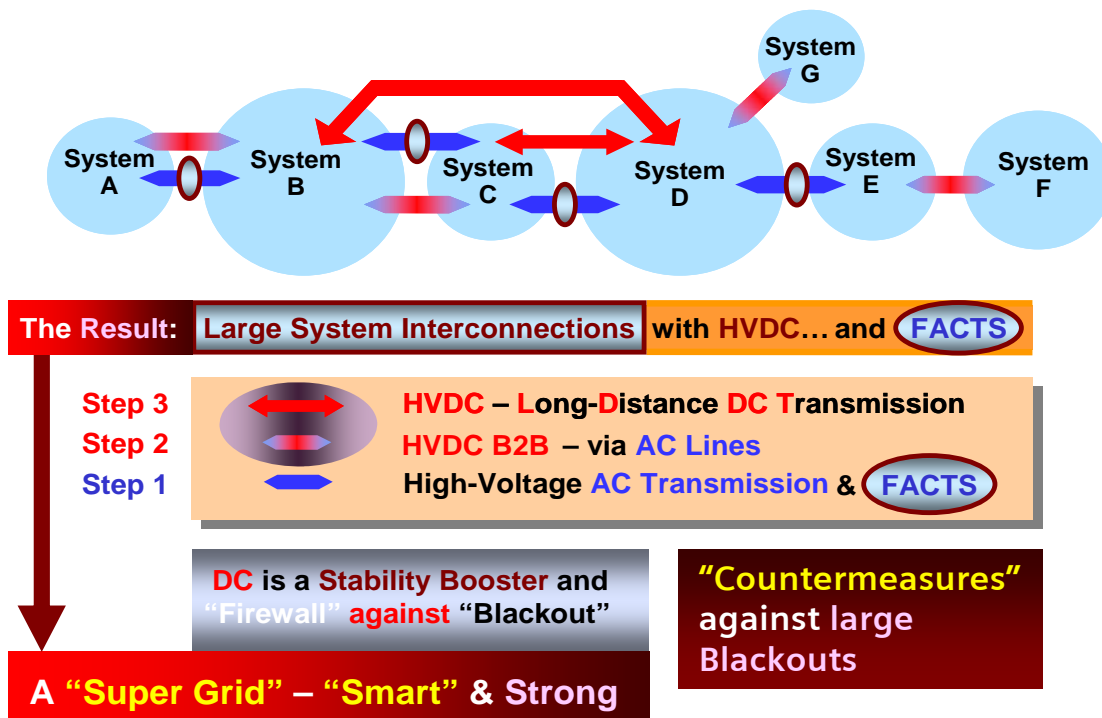


Fig. 19: Hybrid System Interconnections – “Supergrid” with HVDC and FACTS

Based on these evaluations, Fig. 19 shows the stepwise interconnection of a number of grids by using AC lines, DC Back-to-Back systems, DC long distance transmissions and FACTS for strengthening the AC lines. These integrated hybrid AC/DC systems provide significant advantages in terms of technology, economics as well as system security. They reduce transmission costs and help bypass heavily loaded AC systems.

This approach is an important step in the direction of environmental sustainability of power supply [2, 16]: transmission technologies with HVDC and FACTS can effectively help reduce transmission losses and CO₂ emissions.

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SURVEY PAPER - PART 2

INTEGRATED AC/DC TRANSMISSION SYSTEMS – BENEFITS OF POWER ELECTRONICS FOR SECURITY AND SUSTAINABILITY OF POWER SUPPLY

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Abstract – Deregulation and privatization as well as the increase use of renewable energy are posing new challenges on high voltage transmission systems. Environmental constraints, such as energy saving, loss minimization and CO₂ reduction, will also play an important role. The loading of existing power systems will further increase, leading to bottlenecks and reliability problems. High voltage power electronics, such as HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) provide the necessary features to avoid technical problems in heavily loaded power systems; they increase the transmission capacity and system stability very efficiently, and they assist in prevention of cascading disturbances. Therefore, the strategies for the development of large power systems go clearly in the direction of hybrid transmissions, consisting of integrated DC/AC interconnections and point-to-point bulk power transmission “highways” (AC and DC backbones), including FACTS. Such hybrid systems offer significant advantages, both technical and economical as well as in terms of system security. They offer reduction in transmission costs as well as the possibility of bypassing heavily loaded AC systems.

Keywords: *Security and Sustainability of Power Supply; Elimination of Bottlenecks in Transmission; Blackout Prevention; Increase in Transmission Capacity; HVDC and FACTS Technologies*

1 INTRODUCTION

Electric power supply is essential for the survival of a society, like the blood in the body. Lack of power brings about devastating consequences for daily life. However, deregulation and privatization and the increasing share of renewable energy are posing new challenges to the transmission systems. System elements are going to be loaded up to their thermal limits, and wide-area power transmission with fast varying load patterns will contribute to an increasing congestion.

In addition to this, the dramatic global climate developments call for changes in the way electricity is supplied. Environmental constraints, such as loss minimization and CO₂ reduction, will play an increasingly impor-

tant role. Consequently, we have to deal with an area of conflicts between reliability of supply, environmental sustainability as well as economic efficiency. The power grid of the future must be secure, cost-effective and environmentally compatible. The combination of these three tasks can be tackled with the help of ideas, intelligent solutions as well as innovative technologies.

Innovative solutions with HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) 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.

2 HVDC TECHNOLOGIES

2.1 General Development

In the second half of the last century, high power HVDC transmission technology was introduced, offering new dimension for long distance transmission. This development started with the transmission of power in a range of less than hundred MW and was continuously increased (see fig. 1). The development was driven in particular by the needs of power systems with large hydro power plants far away from load centers, e. g. in South America and China.

Transmission ratings of 3 GW over long 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 and further projects with 6-7 GW or even higher are planned.

Since the early 70ies semiconductors were introduced in the HVDC technology. Thyristor based valves were the basis of the development line which today is called “classic” and which is the technology of choice for bulk point-to-point power transmission. It is subject of part one of this survey paper [1].

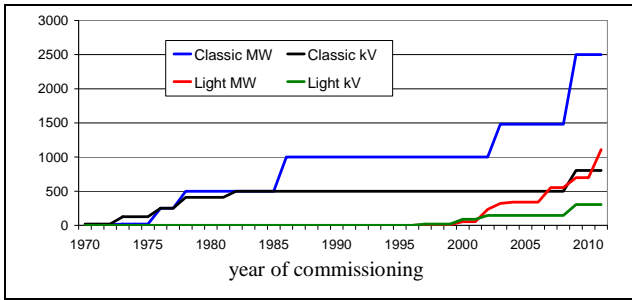


Figure 1: Development of HVDC technology

2.2 VSC High Voltage DC Transmission

Classic HVDC converters are working as current sources, thus also being known as CSC (current source converter) HVDC. Change of load flow direction requires changing polarity of the DC circuit. Therefore and because of voltage peaks during commutation only mass impregnated cables can be used with classic HVDC, e. g. in sub-sea applications.

This was the initial driver for a new development line of HVDC technology, the voltage source converter HVDC (VSC HVDC). It is based on transistors (IGBTs) instead of thyristors. Thus it allows a much better approximation of the sinoid voltage required by an AC system and it allows operation of DC lines with constant polarity independent from load flow direction. Tab. 1 summarizes the main characteristics of the new technology compared to the classic one. 1999 the first system was delivered by ABB. It was a 50 MW transmission system across the island of Gotland, where ABB built the first HVDC system of the world in 1953.

ABB named the new technology HVDC Light[®], indicating both the significantly reduced space requirements for the converters due to the reduced need of filters and the very simply and light XLPE cables which were developed as part of the system. HVDC Light[®] uses pulse-width modulation (see fig. 2), whereas Siemens uses a modular multilevel converter approach [2] for its HVDC PLUS system presented in 2007.

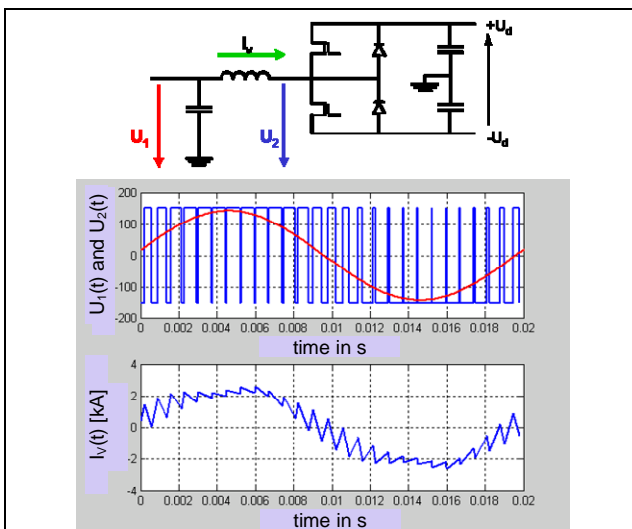


Figure 2: Pulse-width modulation in HVDC Light[®]

	HVDC CSC	HVDC VSC
converter technology	thyristor valve, grid commutation	transistor valve (IGBT), self commutation
relative size	4	1
cable technology	<ul style="list-style-type: none"> oil paper field joints (5 d) sea cable installation with special ship (3 available) 	<ul style="list-style-type: none"> extruded prefabricated land joints (1 d) sea cable installation from barge (> 200 available)
typical delivery time	36 months	24 months
static reactive support	yes	yes
dyn. reactive support	no	yes
independent control of active and reactive power	no	yes
scheduled maintenance	typically < 1%	typically < 0,5%
typical system losses	2,5 – 4,5 %	4 - 6 %
multi terminal operation	complex, limited to 3 terminals	simple, no limitations

Table 1: Comparison of classic (CSC) and VSC HVDC

2.3 Examples of VSC HVDC Projects

Since mid of 90ies of the last century numerous VSC HVDC systems have been installed, many of them benefiting in very different aspects from the various features this technology offers. In the following paragraphs several out of these projects are discussed focusing on the different possibilities of this new technology.

2.3.1 Gotland HVDC Light[®] system

The world's first VSC HVDC project for economical operation was a transmission system commissioned on the Swedish island of Gotland in 1999. Due to wind power generation of 90 MW in the Southern part of this island additional transmission capacity to the Northern part was needed. Additional requirements were minimum environmental impact and compatibility with the rather weak grid on the island. The HVDC Light[®] system installed within the island's grid (see fig. 3) has a capacity of 50 MW.

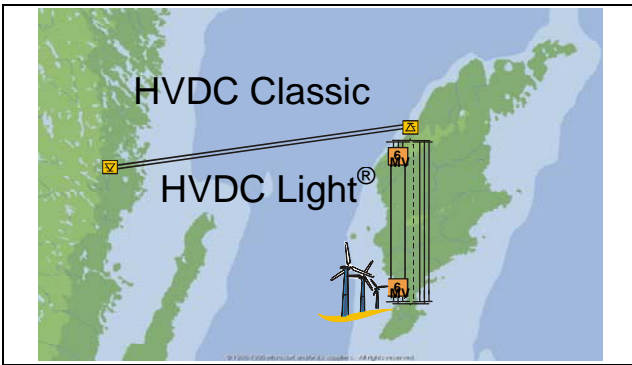


Figure 3: The Gotland HVDC Light® system – the world’s first VSC HVDC system

One of the differences between HVDC Classic and VSC HVDC is the capability of VSC HVDC to provide full SVC functionality by both converters (fig. 4).

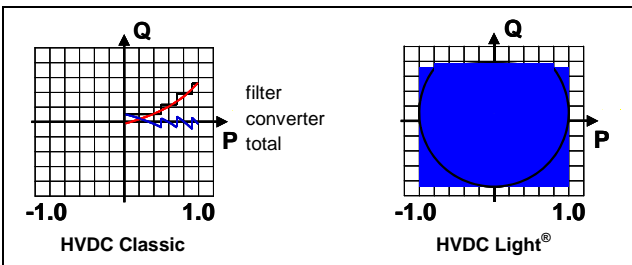


Figure 4: P Q diagram of classic (left) and VSC (right) HVDC – the VSC system can provide any combination of active and reactive power at both converters

This feature makes VSC HVDC ideally suited for the integration into existing AC systems as hybrid solution. In the case of the Gotland project the voltage profile of the existing AC grid could be improved thus increasing reliability of supply on the island and mobilizing additional transmission capacity in the existing grid. This is the reason why the HVDC Light® system has a capacity of 90 MW only although 90 MW wind power were installed. Moreover network losses on the island could be reduced and power quality could be improved despite the doubling of wind power.

2.3.2 Murraylink

Another land cable connection is Murraylink, connecting the grids of Victoria and South Australia with a capacity of 220 MW. With a length of 180 km it is the longest land cable in the world, with about 400 cable joints. Murraylink is in operation since 2002 and has proven an availability of 98,5 % since then, including planned maintenance.

2.3.3 Cross Sound Cable

2003 Cross Sound Cable went into operation. It is a 330 MW HVDC Light® system connecting the grids of Long Island and Connecticut through a 40 km sub-sea cable (see fig. 5). During the big 2003 blackout Cross Sound Cable stabilized supply of Long Island which therefore was not affected.



Figure 5: Cross Sound HVDC link

The purpose of Cross Sound cable on one side is the interconnection of two electricity markets and supply of Long Island with urgently needed electricity and on the other side increased reliability of supply in the Connecticut and New England power systems by improved voltage and reactive power control.

Fig. 6 demonstrated how the Cross Sound cable system stabilizes its environment. The upper graph shows a voltage drop after a line fault in the 345 kV AC grid. A classic HVDC system most likely would fail and need to be restarted under such conditions. The lower graph shows the active power transmitted through the DC circuit. After only 0,15 s the originally transmitted power of 330 MW is reached again thus stabilizing supply on both sides of the system.

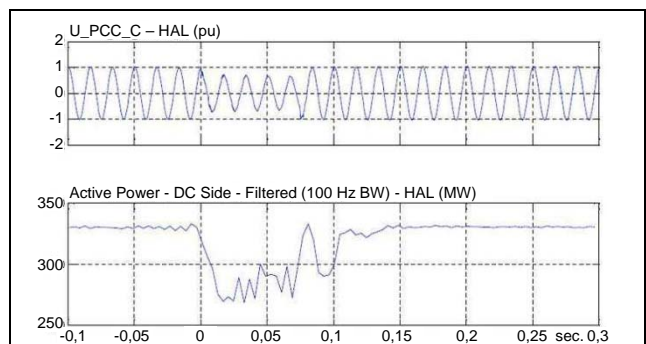


Figure 6: Dynamic response to a line fault in the 345 kV grid on March 17, 2005

2.3.4 Troll A Platform

End of 2004 a project went into operation which highlights a completely different feature of the VSC HVDC technology. For the first time ever a gas platform, the Troll A platform (see fig. 7) within the largest gas field in the Northern Sea, was supplied with electrical energy from land. The traditional way to supply these offshore platforms is by gas turbines on the platform, which is disadvantageous both for safety reasons

and because of the need of operation and maintenance staff on the platform.



Figure 7: Troll A platform with HVDC Light® converter module

VSC HVDC, in difference to the classic solution, does not require any short-circuit power for commutation from the surrounding system. This allows to supply passive loads, a feature, which was used in case of the Troll A platform. Moreover it allows connecting weak grids, e. g. on islands, to a bigger system.

The Troll A system consists out of two 40 MW transmission systems of 70 km length. The HVDC Light® converter on the platform is acting as drive for the motors of the compressors supplied by the system. By this integration, leading to the “longest speed-variable drive in the world”, a very compact design could be achieved on the platform.

Meanwhile, based on the positive experiences, a second supply system for an offshore oil platform is under construction.

2.3.5 Estlink

As one of the priority projects of the European Commission Estlink connects the Estonian power system to the Finnish grid and thus the Nordel system. Estlink was realized as a VSC HVDC system with a capacity of 350 MW, a DC voltage of ± 150 kV, 71 km sub-sea cable and 31 km land cable [3]. It was ordered in 2004 and finished in the end of 2006 after less than 20 months. The reason for this very short delivery time is the high degree of standardization, modularity and pre-fabrication reached since the beginning of the VSC HVDC technology in the 90ies. Moreover the light cables in combination with cable joints that can be set much faster than with mass impregnated cables accelerated delivery. The 71 km of sea cables were laid in ten days only as one piece each.

2.3.6 Nord. E.ON 1

One more feature that differentiates VSC HVDC from HVDC Classic is its black-start capability, i. e. the possibility to start the system without power supply from the surrounding. This in combination with the SVC functionality provided by the converters makes VSC HVDC the ideal solution for connecting offshore wind farms with large distance to the coast to the on-shore grid.

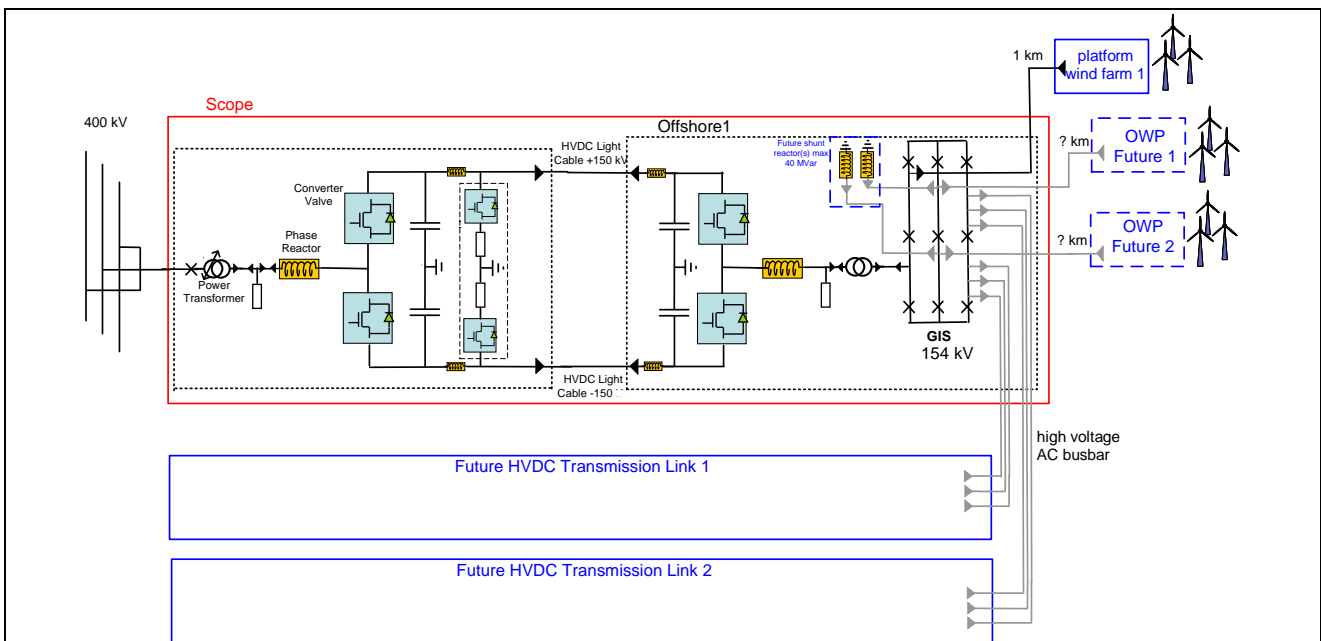


Figure 8: Modular extension concept for Nord E.ON 1 offshore wind farm connection

This was the reason for choosing a 400 MW HVDC Light[®] system when E.ON started to connect the world's largest offshore wind farm cluster called "Borkum 2" to the grid in Northern Germany in 2007. A sub-sea cable of 128 km length and a land cable of 75 km length will connect the existing 400 kV substation at Diele in Lower Saxonia with the first offshore platform for this wind farm cluster. Fig. 8 shows the modular concept by which the system can be extended if further wind farms will be built in the cluster later on.

3 CONCLUSIONS AND OUTLOOK

Since mid of the 90ies a new HVDC technology, the self-commutating voltage source converter HVDC (VSC HVDC) is available and applied in numerous projects. Thus, today there are two technology lines in the market:

- HVDC Classic, based on thyristors, using voltages up to 800 kV and available up to 6-7 GW;
- VSC HVDC, based on transistors (IGBT), using voltages up to 300 kV and available up to around 1 GW.

HVDC Classic is the solution of choice for bulk point-to-point power transmission over long distances. Consequently the main drivers for this development are regions like China or Southern America with large hydro power stations far away from load centers.

VSC HVDC on the other side offers additional benefits beyond power transmission. Its black-start capability, the full SVC functionality given by its converters and the fact that it does not require any short-circuit power from the surrounding networks make it the ideal solution for hybrid applications and for connecting weak islands or passive loads to the grid.

The first VSC HVDC systems were delivered in the late 90ies by ABB with the name HVDC Light[®]. Since 2007 Siemens is offering its HVDC PLUS, which is another VSC HVDC line. Various project examples installed since the beginning of the new technology and partly presented in this survey show the variety of applications and benefits of this technology.

As VSC HVDC is perfectly suited for hybrid applications and integration in existing AC grids, this technology most likely will play an important role in further development of the European power systems. The European Union has set very ambitious targets for climate protection and reduction of CO₂ emissions. Achieving them will require a very high share of renewable energy and thus immediately lead to the question how load and generation can be balanced in such a context.

Analyzing this question with a European perspective, including the Scandinavian hydro power potential, can lead to the conclusion that the solution will be found in regional balancing. If all types of renewable energy would be used where they are available best, Europe would have solar energy coming mainly from the Mediterranean region, wind power from its western coasts and hydro power from its mountains and from Scandinavia. Scandinavian hydro power stations could provide the storage capacity needed in a system with a high share of renewable energy, and regional balancing could be achieved by an HVDC overlay grid with low transmission losses. A scenario developed by ABB and indicating this direction is shown in fig. 9.

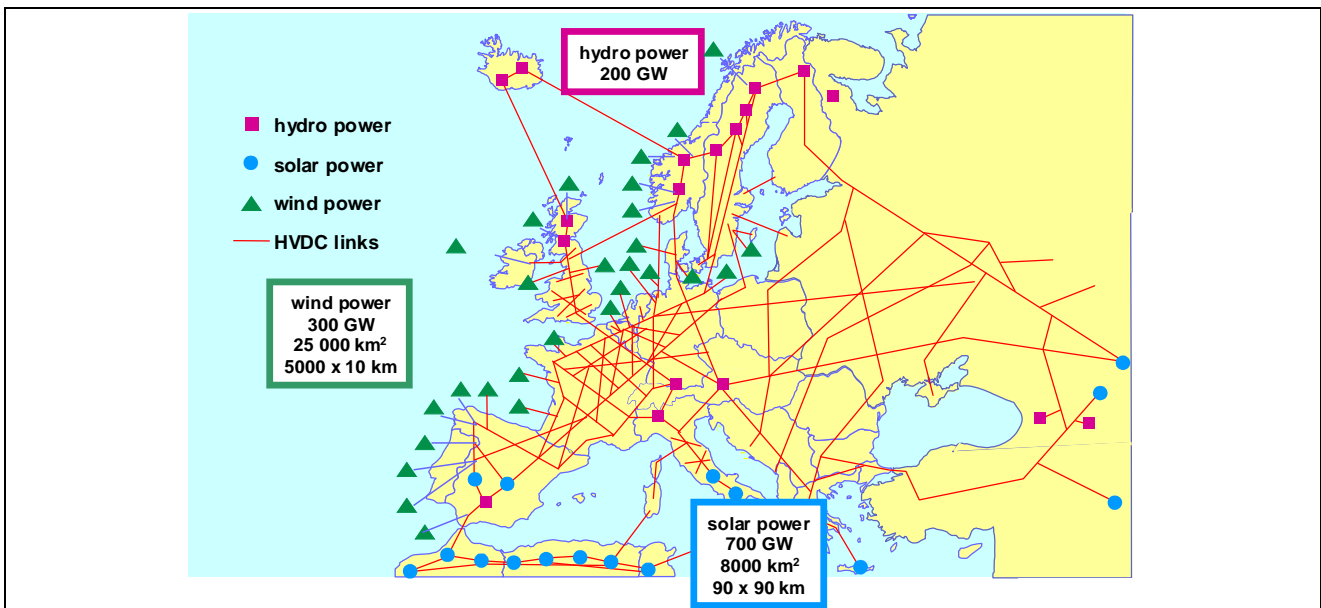


Figure 9: Scenario for a future European overlay grid for regional balancing of renewable energy (ABB)

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