FACTS and HVDC Technologies for the Development of Future Power Systems
X.-P. Zhang, L. Yao, B. Chong, C. Sasse, and K.R. Godfrey

Abstract - The present status and future prospects of FACTS devices and HVDC technologies for modernizing future power systems are reviewed and discussed. The power system across continental Europe is continuing to change due to the integration of renewable energy sources into power grids, leading to the growing need for advanced FACTS and HVDC control with the possibility of integration with wide area stability control and protection systems to prevent cascading outages and system blackouts.

Index Terms - Dynamic Congestion, Dynamic Congestion Management, FACTS, HVDC Converters, SCADA/EMS

I. REVIEW OF PROBLEMS IN PRESENT DAY POWER NETWORKS

In the present day electricity market, electricity companies engage in as many transactions in one hour as they used to conduct in an entire day. Such increased demand along with uncertainty of transactions will further strain power systems. Moreover large amounts of distributed generation, in particular wind generation, connected with the network will result in further uncertainty of load and power flow distribution and impose additional strain on power systems. It is a real challenge to ensure that the transmission system is flexible enough to meet new and less predictable supply and demand conditions in competitive electricity markets.

One of the most common technical solutions in dealing with this challenge is the construction of new transmission lines. However, the process of new transmission line construction is both time-consuming and costly, and may cause short and long-term disruptions to the environment. In addition there are usually many complaints made by neighboring residents, often causing local authorities to disallow planning permission to construct new transmission lines. FACTS (Flexible AC Transmission Systems) devices and HVDC links [1, 2] are considered as low-environmental-impact technologies and are a proven enabling solution for rapidly enhancing reliability and upgrading transmission capacity on a long-term cost-effective basis.

Power flowing in the network is usually uncontrolled, and is governed by Kirchhoff’s laws and Ohm’s law. The uncontrollable power flows may result in low power transfer capability of networks; bottlenecks in the network; loop flows; and angle and voltage instabilities, etc. The power angle and voltage instabilities may cause (a) generator outages, (b) line tripping and (c) system blackouts. Normally an electric power system should be operated within its operating limits such as voltage limits, thermal limits, and angle and voltage stability limits.

FACTS and HVDC can provide both steady state and dynamic control for power systems. For steady state control, FACTS and HVDC can provide voltage regulation; power flow management and control; congestion management; and elimination of bottlenecks and enhancement of transfer capability, etc. For dynamic control, FACTS and HVDC can provide fast voltage support; fast power flow control and dynamic congestion management; fast controlled voltage and power compensation; fast control of power oscillations; voltage stability control; and fault ride-through, etc.

The ever-increasing frequency of blackouts seen in developed countries has also enhanced the need for new power system control technologies such as FACTS devices. Cascading outages are common occurrences before major blackouts. These outages originate from dynamic congestion and shortage of voltage support in the transmission network. The reasons for the blackouts may result from:

(a) investment in the transmission grid has not kept up with the growth in demand and increase in energy trading;
(b) regulatory uncertainty has delayed the investment in the grid and there is a lack of incentives for transmission network companies to upgrade their grids, due to costs and environmental constraints;
(c) in the deregulated electricity market environment, many existing transmission and distribution systems are operated close to their operating limits in terms of voltage, thermal and power transfer capabilities, and system stability constraints;
(d) a lack of fast dynamic control resources such as FACTS and HVDC, which can be used to re-direct power flows among the available transmission corridors, and provide dynamic voltage support;
(e) a lack of coordinated system control via the SCADA/EMS systems;
(f) a lack of sophisticated infrastructure and associated advanced control methodologies that would be able to monitor and control the system wide instabilities across regions.

As FACTS devices can redirect the flow of electricity, they have the potential to relieve or avoid possible congestion and voltage instability. Technologies such as FACTS and HVDC [1, 2], HTS (High-Temperature Superconductor) cable [3], SMES (Superconducting Magnetic Energy Storage) [4] and FCL (Fault-Current Limiter) [5] together with Wide Area
Stability Monitoring, Control and Protection System [6] are available to prevent or mitigate the kinds of outages that have happened in North America and in Europe in the past few years. It is anticipated that with the application of these devices either individually or in combination it should lead to a much more secure and reliable power grid. In addition to the application of FACTS and HVDC in system voltage, power flow and stability controls, FACTS and HVDC will also play a very important role in distributed generation interconnections, voltage and power flow controls of wind power networks, enhancement of the power quality and fault ride through capability, etc.

II. THE CURRENT STATUS OF POWER ELECTRONIC TECHNIQUES, FACTS AND HVDC

A. Power Electronics

Power electronics have a wide spread range of applications from electrical machine drives to excitation systems, industrial high current rectifiers for metal smelters, frequency controllers and electric trains. FACTS devices are just one application besides many others that have followed the same technology trends of power electronics. The history of power electronics started from 1965 with the first Thyristor rectifiers, and development has not stopped since. Power electronics have evolved to the present modularized IGBT, IGCT, IEGT or ETO voltage source converters.

Thyristor

The Thyristor is a device, which can be triggered with a pulse at the gate and remains in the on-stage until the next current zero crossing. Thyristors have the highest current and blocking voltage, and are still the device with the highest voltage and power levels. This means that fewer semiconductors need to be used for each application. Thyristors can be used as switches for capacitors or inductors, and in converters for reactive power compensators. HVDC based thyristor technology is still the only possible AC-DC transmission approach with a voltage level above 500 kV and power above 3000 MW.

These devices are being used in high-voltage direct-current transmission systems. At present, no other device type can match the performance of thyristors, and their application for long distance and large power transmission with very high power is expected to continue in the foreseeable future.

IGCT

To increase controllability, GTO (Gate Turn Off) Thyristors were developed, and can be switched off with a voltage peak at the gate. These GTO based devices are now replaced by IGCT (Insulated Gate Commutated Thyristors), which combine the advantages of low on state losses and low switching losses. These semiconductors are used in smaller FACTS devices and drive applications. The GTO thyristors have also been developed over the past 30 years. Their main advantages over thyristors have been in the higher switching speed and the ability to turn off the current without reversal of the anode to cathode voltage. These attributes have led to the use of GTOs in high power inverter systems.

IGBT and IEGT

The IGBT (Insulated Gate Bipolar Transistor) has become an important power electronic technology in FACTS applications. The device takes advantage of the high voltage bipolar transistor with MOS gate. Basically an IGBT can be switched on with a positive voltage and switched off with a zero voltage. This characteristic allows a very simple gate drive unit to control the IGBT. The voltage and power level of the applications is up to 300 kV and 1000 MVA for VSC HVDC.

IEGT (Injection Enhancement Gate Transistor) chips are the latest in fast recovery diode technology, and are an advanced standard package design. They create a compact, high-efficiency and high-isolation 6.5kV, 1.2kA IEGT module, which uses trench gate semiconductor technology. The IEGT has high power ratings comparable to the GTO and can be operated at high speed comparable to the IGBT. The latest IEGT module combines low thermal resistances with reduced on-state losses and a 30% reduction of off-state losses is realized when compared with conventional modules. In addition, the size of an IEGT module is about one third of that of a GTO module.

ETO Thyristor

An ETO (Emitter Turn-Off) thyristor combines the best characteristics of IGCT and IGBT with a high current carrying capability and a medium voltage of GTO is considered as one of the emerging high-power semiconductor devices. The ETO Thyristor was initially developed as an extremely high-power switching device to be used in power conversion systems within electric utility grids. The ETO Thyristors are capable of switching up to 4 kA of electric current and 6 kV of electric voltage. The ETO Thyristor has the following technical characteristics:

(a) 5000A snubber-less turn-off capability;
(b) low switching losses & conduction losses;
(c) low cost device and circuit;
(d) easy for series and parallel operation;
(e) low gate drive power;
(f) built-in over-current protection and current sensor;
(g) easy for mass-production.

B. FACTS and HVDC Controllers

There are two categories of FACTS devices available. Thyristor switched and/or controlled capacitors/reactors such as SVC (Static Var Compensator) and TCSC (Thyristor Controlled Series Compensator) were introduced in the late 1970s while Voltage-Sourced Converter-based FACTS devices such as STATCOM (Static Synchronous Compensator), SSSC (Static Synchronous Series Compensator) and UPFC (Unified Power Flow Controller) were introduced in the mid 1980s. In the past, there has been a large number of SVCs installed in electric utilities. There are tens of conventional line commutated BTB (Back-to-Back) HVDC, a number of STATCOM and TCSC, three UPFCs,
one IPFC and a number of VSC HVDC with BTB configuration installed within electric power systems around the World. It is anticipated that more STATCOM and VSC HVDC will be installed in the future.

All FACTS devices and HVDC links are helpful in stability control of power systems. The shunt type FACTS device is more useful to control system voltage and reactive power while the series type FACTS device is more suitable for power flow control. The series-shunt type controller - UPFC can be used to control the active and reactive power flow of a transmission line and bus voltage independently. The series-series type FACTS controller – IPFC (Interline Power Flow Controller) can be used to control power flows of two transmission lines while the active power between the two transmission lines can be exchanged. The newly developed VSC HVDC, which has similar control capability as that of the UPFC, can control both the independent active and reactive power flows of a transmission line and the voltage of a local bus [7]. However, the HVDC based conventional line commutated converter technique cannot provide voltage control and independent reactive power flow control. Another very important feature of VSC HVDC technique is that it can be very easily configured into a multi-terminal VSC HVDC. Research indicates VSC HVDC is a viable alternative to the UPFC for the purpose of network power flow and voltage control.

FACTS devices based on VSC techniques can be interconnected to implement various configurations and structures for different control purposes. While thyristor switched and/or controlled capacitors/reactors have limited performance and functionality, converter-based devices have superior performance, versatile functionality and various configuration possibilities. One shortcoming with converter-based devices is, they are more expensive. With the continuing effort in R&D, it is likely that the costs of converter-based devices will be reduced further, and hence they will be more widely used in the next 5 years.

III. FACTS AND HVDC CONTROLS OF THE FUTURE POWER SYSTEM IN EUROPE

A. The Trend of the Future Power System in Europe

Although by year 2020, according to the EU target, around 20% of the total energy will be from renewable energy including wind power, conventional power resources such as fossil fuel, nuclear and hydro, will still dominate energy production. With increasing gas and oil prices, it is anticipated that more nuclear power plants (for instance in the UK, France, and Germany) will be constructed to shoulder the base load. The penetration of distributed generation including wind power with an intermittent nature is expected to increase significantly and impose extra constraints on the interconnected system. Distributed generation, in particular, wind generation with a fluctuating and intermittent output will not significantly reduce the power transfer requirement, rather, it will require a stronger transmission network and enough reserve from conventional power plants to support the system voltage, balance the generation and demand, and ensure that load centers can be supplied by conventional power when renewable generation is unavailable. It is quite common that large load centers may not always be close to the power generation sources. Therefore, power needs to be transferred from the generation sources to the point of consumption through the transmission network. This indicates that even in the situation where distributed generation is increasingly integrated to power grids, a strong interconnected transmission network is still needed.

Based on national resources available and energy strategies different EU countries have a different mix of energy resources. For instance, in France, there is large-scale nuclear power production, and it is likely that more nuclear power plants will be constructed. In the European electricity market environment, electricity trading will be made across different countries. This will impose further stress to the already constrained interconnected network. The blackout in Italy in 2003 is an example of such a consequence.

Considering the development of renewable and conventional energy resources and increased power transfer resulting from electricity trading across different countries, a super power grid across the regions/countries may be needed using advanced HVDC and FACTS technologies. It remains to be seen whether this super grid will consist of a single large grid that will be linked and synchronized more tightly, or whether it should consist of a number of independent sub-grids coupled by back-to-back DC links. Currently a super AC power grid with a voltage up to 1000 kV is being planned in China, and in the US, a super power grid using superconducting DC transmission is being discussed.

B. Needs of Advanced FACTS and HVDC based Control for Future Power Systems in Europe

It has been recognized that some transmission systems are not yet designed for the deregulated energy market. Power system infrastructure needs modernization as future power systems will have to be smart, fault tolerant, dynamically and statically controllable, and energy efficient. As discussed in the previous section, the interconnected transmission network needs either to be enforced or to be upgraded to a super power grid using FACTS and HVDC technologies. The super power grid may be a mixture of high voltage AC and HVDC links plus FACTS devices for provision of secure and reliable power transmission.

FACTS and HVDC will be helpful to provide fast dynamic voltage, power flow and stability control of the power grid while enhancing efficient utilization of transmission assets. At the same time network congestion will be efficiently managed and system blackouts will be mitigated or avoided.
C. Advanced FACTS and HVDC Control for Security Operation of Large Transmission System

Coordinated power flow, voltage control and congestion management:

There may be a need to manage grid security and power flow using an increasing number of power and voltage controllers with greater capacities, therefore system operators must be able to implement coordinated controls across the different European transmission grid company owners.

Coordinated dynamic power flow, voltage control and dynamic congestion management:

Dynamic congestion management becomes increasingly important as more and more distributed generation resources are being introduced to electricity grids, where fluctuations of power distributions across the networks are common. In this situation, fast dynamic management of power flow to relieve congestion in the networks and fast voltage control and reactive power balancing and possibly active power balancing in electricity market environment is vital to the success of future electric power systems using FACTS and HVDC.

D. Integration of Wind Area Stability Control and Protection with FACTS and HVDC Control against System Blackouts

The wide area stability control and protection system is considered the “eyes” that overlook the entire system area, and can capture any system incidents very quickly; while FACTS and HVDC are the “hands” of the system, which have very fast dynamic response capability and should be able to take very quick actions as soon as commands are received from the system operator. As the current situation stands, the fast dynamic control capability of FACTS and HVDC has not been fully explored and realized. The integration of the Wide Area Stability Control and Protection with FACTS and HVDC control will fully employ control capabilities of both technologies to achieve fast stability control of system, and to prevent the system against blackouts. Hence, a high network security and a reliable performance can be achieved.

In order to tackle large-scale stability disturbance and protect the transmission system against blackouts, a coordinated control of the integrated power network is required using the advanced stability control methodologies and/or wide area monitoring and control by using FACTS and HVDC control technologies. In order to fulfill the requirement of wide area monitoring control, Phasor Measurement Units (PMU) are required to be installed in some portal substations, which can provide necessary information for wide area control. In addition, a system operator of the interconnected EU network is essential to coordinate the operation and control of the system reliably and safely.

E. FACTS and HVDC for Distributed Generation

FACTS and HVDC can be applied in transmission systems to improve the voltage, power flow and stability control. They can also be applied in the interconnection of distributed generation to power grids in order to satisfy the connection requirement of distributed generators in compliance with the Grid Codes. In recent years, a number of VSC HVDCs with BTB structure have been applied in the wind generation interconnection with the grid thanks to the voltage, active and reactive power control capability provided by the BTB VSC HVDC. In the future, for some applications, a multi-terminal VSC HVDC configuration may be used.

In Europe, distributed generation, mainly wind generation with an intermittent nature, will add challenges to the operation and control of the interconnected power network. FACTS controllers such as SVC and STATCOM can be applied to control voltage of wind generators, as voltage usually fluctuates. STATCOM, which has the ability to regulate voltage smoothly and quickly and provide continuously dynamic reactive support, will find wide application in this aspect. STATCOM integrated with energy storage will give the device greater influence such that dynamic active and reactive power flow control may be achieved.

STATCOM and SSSC devices can be used to achieve voltage and power flow control for wind generation, power quality control for preventing voltage dips; voltage swells; fault ride through and stability control.

In order to fully employ the capabilities of FACTS, use of the energy storage integrated with FACTS will be a viable solution in providing multifunctional controls for voltage fluctuations, power flow and power quality in a single device.

IV. FUTURE DEVELOPMENT OF FACTS AND HVDC

The development of future FACTS and HVDC requires:
(a) reduction of overall costs
(b) improvement of reliability
(c) structural modularity and scalability
(d) mobility and relocatability
(e) internal fault-detecting and protection capabilities
(f) openness to third party product connectivity

A. Reduction of Overall Costs

It seems likely that continuous R&D effort will reduce the overall cost of VSC by 25 to 30 %, because no auxiliary components are needed for harmonic cancellation; transformer-less series controllers can be developed; identical building block module structure for partial availability can also be developed; wide-frequency band control operation will become fast and effective; and protection action during abnormal operation conditions and contingencies will become feasible.

B. Improvement of Reliability

With the advances in IEGT, ETO or other power electronic switch techniques, reliability will be improved due to the application of simplified circuits and advanced packaging techniques. As there are an enormous number of chips in a power system converter, a single chip failure would not lead to malfunction of an entire FACTS device.

C. Structural Modularity and Scalability

The concept of modularity comes from computer software
engineering; modularity has been applied to hardware architecture, institutional organization and structure, etc. A modular design should have a clear architecture, clean interfaces, and a set of well-specified functional tests of each module’s performance. The design of IBM’s 360-mainframe computer is a good example for explaining modularity. The IBM system was designed to have various parts, called modules. The modules were designed and produced independently of one another, but, when combined, they worked together seamlessly. As a result, all mainframe computers built out of the 360 modules could run the same software. Furthermore, new modules could be added to the system, and old ones upgraded without rewriting code or disrupting operations.

The H-bridge Building Block is a modular-designed VSC, which has easy-to-expand voltage and power ratings by adding building blocks in series or shunt connections. Modular design of VSCs will therefore be convenient for maintenance and easy to diagnose for fault or failure of hardware.

Scalability is a very important design concept in electronics systems, computer systems, databases, routers, and networking; it implicitly implies performance. A system, whose performance improves after adding hardware, proportionally to the capacity added, is said to be a scalable system. System scalability makes system expansion simple and easy, hence upgrading the system is more feasible.

D. Mobility and Re-locatability

In electricity market environments, the uncertainty of the system demand becomes a real challenge. In this situation, it is preferable that FACTS devices can be mobilized and should be relocatable according to the system demand distribution. In this way, the stranded transmission investment costs may be avoided, and hence the uncertainty of planning can be hedged. A relocatable GTO based SVC comprising of TSC, STATCOM with an output of +225/-75 MVar, (the first of its kind), was commissioned at the NGE East Claydon substation in 1999 [8]. The layout of the relocatable GTO based SVC is shown in Fig 1.

E. Functional Flexibility

Functional flexibility requires a FACTS device to provide more than one control function or control possibility. In addition, the FACTS device should be expandable to realize interconnections with other FACTS devices or storage devices. For instance, two STATCOMs may be configured into either a BTB VSC HVDC or a UPFC.

F. Connectivity and Openness to Third Party Products

Connectivity requires FACTS and HVDCs with the ability to provide possibilities to connect with other power system control devices. In addition, the control systems of the third parties need to be easily interfaced with SCADA/EMS systems via communication infrastructure.

Similar to that of a computer, a FACTS device should have the possibility to be integrated with third party products. Plug-and-play interconnection of FACTS and HVDC within transmission systems will be a very important characteristic of the future FACTS and HVDC technologies.

G. Hybrid FACTS Controllers

Due to the high cost of FACTS devices, hybrid FACTS may be constructed by combining traditional devices with FACTS devices in order to expand functionality. For instance, a Quadrature Booster (QB) transformer may be combined with a TCSC to realize independent active and reactive power flow control.

H. Intelligence-Based Monitoring and Diagnostic System for FACTS and HVDC

An intelligence-based monitoring and diagnostic system for FACTS and HVDC will be able to monitor and diagnose any early warnings for potential failure of power electronic components, and therefore corrective actions may be taken before any malfunctions occur.

V. CONCLUSIONS

This paper presents a review of problems experienced by power systems of today, and the current status of applications of power electronic techniques such as FACTS and HVDC in power systems. The needs of advanced FACTS and HVDC techniques for control of future power systems in particular are described and addressed.

In order to ensure that the transmission system is flexible enough to meet new and less predictable supply and demand conditions, the interconnected power system should be modernized and transformed into a smart power grid, which is an intelligent, electronically controlled power system in comparison to the electromechanically controlled system used today. A modernized electricity system will enable a substantial increase in productivity, improve energy efficiency and resource utilization, and generate significant additional wealth to meet the growing societal and environmental needs of the twenty-first century.

The key technologies required for control of future power systems will include advanced intelligent sensing, advanced
communication hardware for monitoring and control (including wide area based system monitoring and control systems), data-processing, advanced power system operation and control software, FACTS and HVDC to reduce congestion, fast reaction within real-time to mitigate disturbances, provide fast voltage support, and redirect the flow of power when necessary. The primary control objectives of future power systems are:

(a) to facilitate electricity trading;
(b) to optimize the overall performance and robustness of the system;
(c) to react quickly to disturbances to minimize their impact and prevent the system against blackouts and;
(d) to restore the system to the normal operating level after a disturbance.

FACTS and HVDC solutions together with advanced communication, computing and control technologies will fulfill the above requirements. With the continuous effort in R&D of control technologies, it is likely that the costs will be further reduced, and hence they will be more widely used in electric power grids in the next 5 to 10 years.

VI. REFERENCES


VII. BIOGRAPHIES

Xiao-Ping Zhang (M’95) received the B.Eng., M.Sc., and Ph.D. degrees in electrical engineering from Southeast University, China, in 1988, 1990, 1993, respectively. Currently, he is a Lecturer in the School of Engineering, University of Warwick, Coventry, U.K. He was with Nanjing Automation Research Institute (NARI), Ministry of Electric Power, China, working on EMS-EMS advanced application software research and development from 1993 to 1998. Dr. Zhang was an Alexander-von-Humboldt Fellow at the University of Dortmund, Dortmund, Germany from 1999 to 2000.

Liangzhong Yao received the M.Sc and PhD degrees in electrical engineering from Tsinghua University, China, in 1989 and 1993 respectively. He was a senior power system analyst in the Network Consulting Group at ABB Ltd in the UK from 1999 to 2004. Currently he is a Technology Consultant working on wind power and network design and consulting at AREVA T&D Technology Centre in Stafford, UK. Dr. Yao is a Chartered Engineer and a member of the IEE.

Beatrice Chong received the M.Eng degree in electrical engineering from University of Warwick, U.K., in 2004. Currently, she is a Ph.D student in the Systems Modeling and Simulation Research Group in the School of Engineering, University of Warwick, Coventry, U.K.

Christian Sasse is the General Manager for the AREVA T&D Technology Centre in Stafford, UK, and has been responsible for the R&D programme of distributed power, coordinating and managing research activities in wind energy, fuel cells, biomass, energy storage and solar energy in the UK and in Europe. In May 2005 he was elected as Chairman of the EC Technology Platform for Electricity Networks of the Future, in preparation for Seventh Framework. He obtained his MSc in Physics at the University of Karlsruhe in 1986. He completed a Ph.D. in optical light scattering in solar heated fluidised beds in 1992 while working at the German Aerospace Centre in Stuttgart in the area of Solar Thermal Engineering.

Keith Godfrey (B.Sc., Ph.D., D.Sc., C.Eng., FI EE) is a Professor and Head of the Systems Modeling and Simulation Research Group in the School of Engineering at the University of Warwick. Recently, he has been awarded the IEE Smell Premium (2000), and the Honeywell International Medal (2000/2001) of the Institute of Measurement and Control for distinguished contributions in the areas of identification and control of dynamic systems. He is a member of the IFAC Technical Committees on Modeling, Identification and Signal Processing, and on Biomedical Engineering and Control.