Study of FACTS and DFACTS in China

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Abstract - This paper gives a short description of the state-of-art of FACTS and DFACTS study in China. Based on the experience in the development of China's first 20Mvar STATCOM, the authors lay the stress on the performance differences between the FACTS and DFACTS inverter and that of the conventional industrial ones due to the diverse operating conditions. This gives an engineering insight into the operation of FACTS and DFACTS devices.

Keywords: STATCOM, ASVG, DVR, Active Filters, FACTS, DFACTS

1. Introduction

At the threshold of the new millenium, the pace of information technology (IT) advances seems overwhelming. IT is penetrating all sectors of business, industry and human life, and has been radically and fundamentally altering our life form as well as the mode of management, and approach to production. The operation of information age is unprecedented dependent on the quality of electric energy supply, and brings huge challenges to the electric power industry. Among many factors affecting the quality of electric power supply the most critical ones are

--- Multifarious new power conversion devices and portable rechargeable energy source,

---The security, reliability, low price, and high quality of energy service,

---The suppression of evergrowing power electronic pollution.

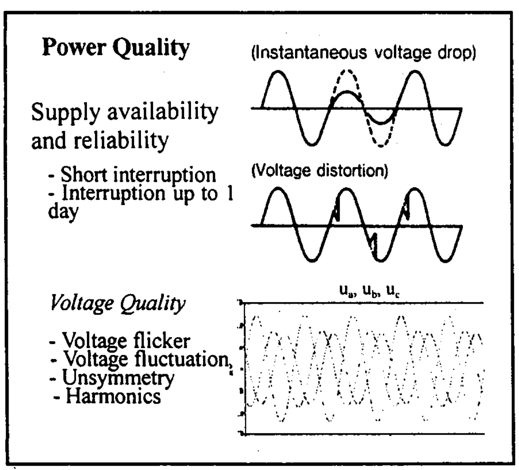

Fig.1 Power Quality

Fig.1 gives the main aspects of power quality, and Fig.2 shows the possible economical loss caused by voltage sag due to the power quality problem.

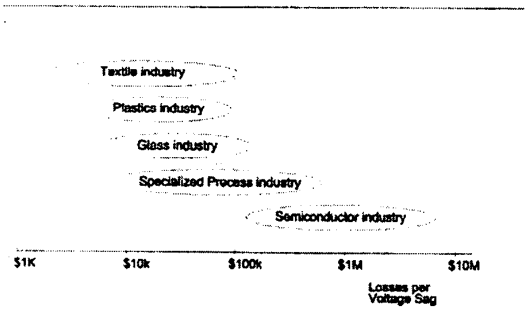

Fig.2 Influence of Power Quality on Customer

As new upgrade technologies, FACTS and DFACTS provide an effective approach to control the power flow and to improve the security, economy and quality of electric power supply by rapid adjusting the system parameters.

Dr. Hingorani is credited with originating the concept of FACTS [1,2]. Such a concept is aimed at reconstructing the traditional power system by introducing power electronics technologies to make it more flexible and reliable. Since it proposed in 1986, many kinds of FACTS controllers for different parameters regulating and in different configurations have been developed. Fig.3 shows the functions of some principal FACTS devices.

As the expanded use of FACTS, DFACTS brings the solution for "Custom Power" or power quality problems at the user-end [3].

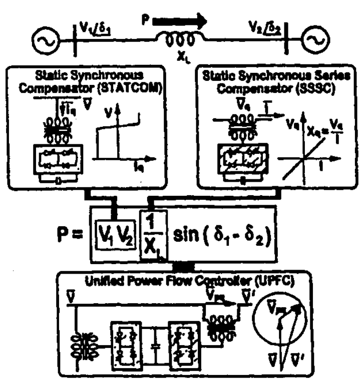

Fig. 3 Functions of FACTS Devices

According to the statistics both the installed generating capacity and the annual electricity generation of China now have ranked second in the world, but the per capita in stalled generating capacity is about 0.25kW only. This number is far less than that of the developed countries, and ranked between 70th and 80th in the world. In general China is still a country lacking of electricity.

Moreover, because of uneven distribution of energy resources, i.e. 90% hydro potential located in west part and 80% of coal deposits situated in the north part, while 70% energy consumption concentrated in the east and south part of china, bulk power and long distance transmission are the inevitable results. However the weak network configuration due to lack of parallel line brings about the problems of low reliability, the available transmission capability of existing lines in China is set by stability limits, rather lower than their thermal limits. The big gap between the stability and the thermal constraints open up the possibility for maximum the transfer capability by suitable FACTS application. In addition to that, the electromagnetic loop network, which is comprised lines at different voltage grades, is still existing in China power system. Hence, there is a pressing necessity for restructuring the existing network to enhance the operating security, to increase the allowed capacity of transmission networks. And those challenges facing China electric power industry offer the best opportunity for FACTS application. Along with the advance of new technologies and information industry, the power quality has also gained more and more attention. It could be foreseen that with the further evolution of electricity market and the progress of legislation in power quality, the reconstructed urban power network would rely on the application of new technology including DFACTS to improve its electric power supply.

2. The FACTS and DFACTS Study in China

Chinese electric engineering industry and utility have been paying close attention to the application of power electronics in the power system. In late 1970s, the static excitation system based on thyristor rectifier has been widely used in China generation plants. In 1986, the researchers in Tsinghua University applied the Linear Optimal Control Law to the excitation controller of a 100Mvar hydro-generator. This system was then experienced field test, and demonstrated the superiority of such a control system over conventional PID controller. It is the first time in the world to apply LOC to the exciter control of an actual industrial generator. In 1985, the researches in Northern Electricity University developed China's first laboratory model of Advanced Static Var Generator based on thyristors. The research and experimental results were attributed as China's firstling in this field [4].

In 1994, Tsinghua University and Henan electric Power Company made an agreement on cooperative development of China's first 20Mvar STATCOM. This project represents the commencement of China's FACTS development program in engineering application field. And it was then ranked as the key research project of Chinese Electric Power Ministry (CEPM), and obtained prevalent concern in the electrical engineering trade. In 1996, as the fruit of first stage, the 300kvar prototype STATCOM based on GTO was put into operation in Zhengzhou, Henan province [5]. Good static and dynamic characteristics demonstrated in field test show the effectiveness of STATCOM in improving system performance and the correctness of system design. After several months test-run it passed the technique appraisal organized by CEPM. In March 1999, the 20Mvar STATCOM was successfully put into service at Chaoyang 220KV substation, Henan province [6]. It signifies the important step taken by Chinese technologists in the FACTS development. China is then after USA, Japan and Germany as the fourth country mastering the key technologies in manufacturing 10Mvar-scale STATCOM. Fig. 4 is the one-line diagram of 20Mvar STATCOM, and Fig. 5 shows the photo of the 20Mvar STATCOM.

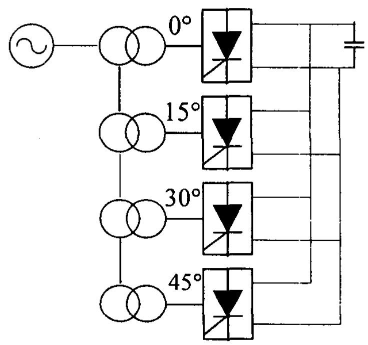

Fig.4 20Mvar STATCOM Configuration

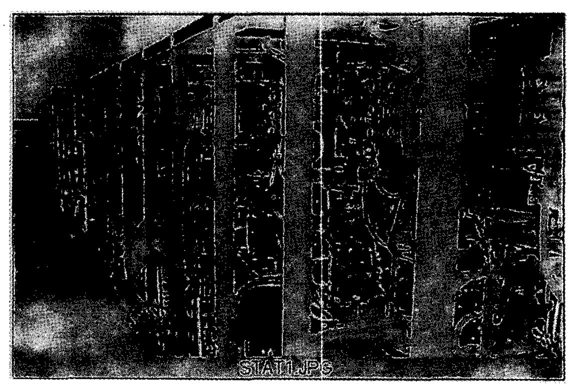

Fig.5 Photo of STATCOM

And Fig.6 is the response curves from zero reactive power output to 20Mvar output, it shows the good

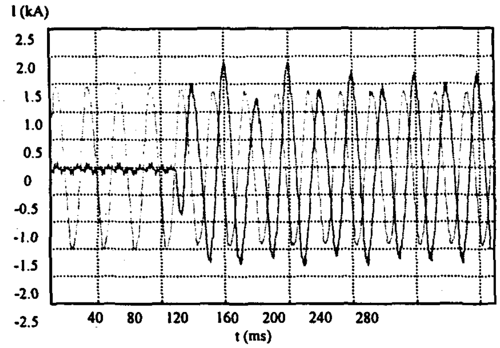

Fig.6 Response of 20Mvar STATCOM

dynamic performance of device. In 1996, under the cooperation of Electrical Power System Research Institute of China, Tsinghua University, Shanghai Jiaotong University, and Dongnan University together with Northeast Electric Company, began a joint research project of TCSC under the support of Chinese National Natural Science Fund. Among them, the investigation of the over-voltage isolation was performed in Electrical Power System Research Institute of the China Power Ministry. The dynamic physical model of thyristor based TCSC was implemented and tested in Tsinghua University. The Shanghai Jiaotong University focused on the SSR problems. Recently, the investigated results of TCSC are finalizing.

The Chinese technologies are concerned with not only the development of the FACTS devices, but also the "Custom Power". As early as late 1970s, the researchers in the department of electrical engineering of Tsinghua University had engaged in harmonic compensation study. They performed the harmonic analysis for Anshan and Baoshan Steel Companies respectively, and designed corresponding harmonic filter for them. Since 1990s, Harbin Engineering University and Xian Jiaotong University etc. ploughed into the development of Active Power Filter, successively. In order to put the investigated results of STATCOM into solution of the power quality problems in the distribution system, since 1997, Tsinghua University and University of Macau have begun to cooperate in the study of DS-UniCon (Distribution System Unified Conditioner). DS-UniCon is a system, which can be used not only to compensate the harmonics, reactive power and unbalanced problems but also the power interruption. Battery Charger System and 3-level IGBT based Converters are used. However, DS-UniCon is proposed to compensate all the power problems in the "Custom Power" in order to improve the power quality, reliability and security. Fig.7 gives the circuit configuration. In 1999, a 15kVA Shunt 3-Level IGBT Base Converter was settled up and tested for DS-UniCon. However, combined model of DS-UniCon is investigated in progress [7].

The fast-growing economy of China offers the good opportunities for the development and implementation of

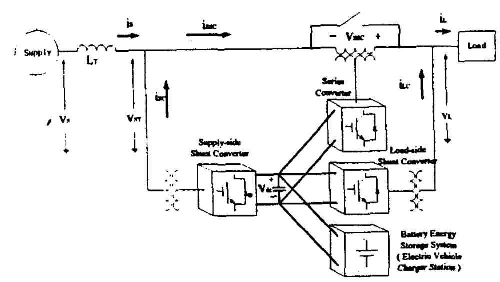
Fig.7 One-line Diagram of DS-UniCon

FACTS and DFACTS technologies, and provides a large stage for China's electric and electronic engineers to display their talents.

3. Some Special Issues of FACTS and DFACTS

The basic configuration of a 2-level three-phase voltage source converter is considered, where six self-commutated switching devices, such as GTOs, are applied together with six corresponding anti-parallel diodes. With the switching actions, the converter experiences "charging", "free-wheel" and "discharging" three modes. Through adjusting the relationship among three modes, i.e. the switching timing of the gate pulse, the directions as well as the quantities of the active power and the reactive power exchanged between the power system and the converter [8] can be controlled. However, as used in power system, the converter presents some peculiarities, and will be addressed hereafter.

3.1 Narrow Controllable Angle

In steady state, the output reactive power of STATCOM may be given in per unit form as:

$$Q_0^* = -\frac{V_S^{*2}}{2r^*}\sin 2\delta$$

With $Q_o^* = 1.0, V_s^* = 1.0$, and $\sin 2\delta_o \approx 2\delta_o$ for a high power STATCOM, above equation may be reduced to $|\delta_o| = r^*$ This indicates that the control angle of rated condition is equal to the per unit value of active losses of STATCOM [9]. For high power device, r^* is in the order of 2 or 3%, the corresponding δ_0 is about only several degrees. This implies STATCOM has a very high rate of change of output reactive power with control angle, the high change rate increases the difficulties in the accurate control of the output reactive power. In addition to that, the small coupling reactance further magnifies the demands for a fast and high reliable over-current protection system.

3.2 Severe synchronizing requirement

Above discussion shows that the operation of FACTS device involves the power exchange between two ac power sources, through series or shunt coupling reactors. The same as in the case of the parallel operation of synchronous generator, the smooth starting and stable operation of the FACTS inverter requires the synchronization of the output voltage with the system. However, the impedance of the STATCOM is smaller than that of the generator. That means over-current will be more easily caused by slightly not synchronizing for STATCOM and a more severe synchronizing requirement for STATCOM. The phase-locked loop and zero-crossing detection technologies are generally adapted to obtain the synchronizing signal for control. The response time of these synchronizing approaches is about 20ms or longer. If the voltage of the power system varies slowly, the STATCOM can operate very well with these approaches. However, if the voltage varies fast, the STATCOM will be easily over-current. Within the development of 20Mvar STATCOM, a high precision pulse generating board with new synchronizing method based on "Fictional Rotor Algorithm"[10,11] with response time less than 3ms has been developed. It improves the viability of STATCOM under fast variation of the system voltage.

3.3 Multi-Level Configuration

The basic configuration of multi-pulse converter is to realize the series or parallel connection of several basic single-bridge converters via zigzag connected magnetic transformer. In practice, transformer is bulky, expensive and inefficient, more than that its nonlinear magnetizing characteristics may result in over-current and over-voltage in converter, eliminating the requirement of such a transformer means a great save in both cost and space. However, it is still the most popular practice in high power converters, because they provide the most efficient harmonic eliminating strategy and the effective output voltage control.

The newly developed "Chain Circuit Converter" [12], which is constituted with a series of identical single-phase voltage source converter, as shown in Fig.8, can increase the rating of the equipment simply by adding the number of chain links in series, and eliminating the requirement for dc voltage balancing. It provides unprecedented possibility for the development of high voltage, high power converter. However, the requirement for separated dc source leads to a complex configuration while the active power exchanging involved.

3.4 Ferromagnetic Nonlinear and Its Effects

FACTS device is normally connected to the power system via coupling transformer. Because the ferromagnetic core of transformer consists a significant nonlinear, the connections of transformer windings and the type of magnetic materials determine the shape of the flux wave. In FACTS device, such a nonlinear may effect the performance in two ways, the first one is the dc-magnetization, which has been addressed by many authors. Because the transformer is connected with a voltage source converter, when a dc component is contained in the output ac voltage of converter, it will arise an erratic dc current in the converter winding of the

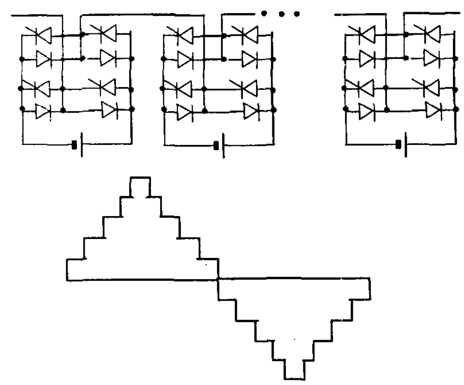

Fig.8 Multilevel Converter with Separated dc Voltage

transformer, and finally drive the transformer into saturation. In addition to that, under major disturbance the high surge current involved in the switching-in process of large parallel load will also drive the core of transformer quickly into saturation, a fast acting compensation block should be adapted to suppress the transient dc component of the converter output voltage. A control scheme adapted by Toshiba [13] is given in Fig.9.

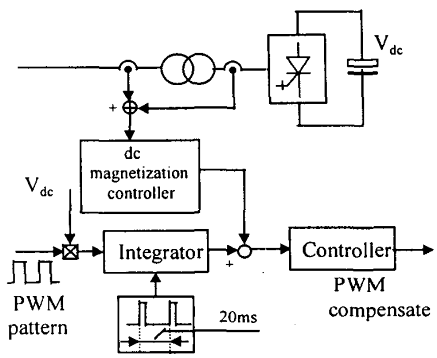

Fig.9 DC Magnetization Preventing Controller

The second one, which is seldom mentioned, is the distortion of the magnetizing current, and hence the induced ac voltage. In zigzag-connected transformers, non-sinusoidal ac voltages may be measured at the terminal of converter windings, Fig.10.

The reason is that although the applied external system voltage is sinusoidal, there exists no restriction to the shape of the flux, and hence the induced voltage of each transformer. Each small difference in parameters and phase shifts may bring each transformer operating in different point in its magnetization curve, thus the generated waveforms of flux, and hence the induced voltages may be quite different. It may result in serious distorted induced ac voltage, and abnormal dc voltage rise [14]. Above problem may be solved by reducing the nominal flux density in the core, however it may significantly increase the size as well as the cost of

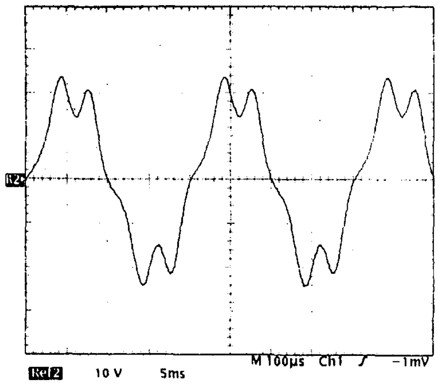

Fig.10 The Test Waveforms of a Zigzag Transformer Secondary Winding

transformer, or by providing a circuit for the harmonic component of the magnetizing current with an additional load resistor. In our 300Kvar STATCOM with an inserting parallel resistor of 0.01pu, the dc over-voltage is reduced from 1400V to 600V in pulse blocking. Above discussion indicates that the designers should be very prudent in the use of ferromagnetic materials.

3.5 Harmonic Resonance

The simplified equivalent one-line circuit of STATCOM is shown in Fig.11, it contains inductive and capacitive components, which, under certain conditions such as distorted line voltage or non-sinusoidal modulation function, will cause resonance. Such a harmonic resonance may result in serious oscillation in both DC voltage and AC currents, which may damage the device, and limit the exertion of the capability of STATCOM.

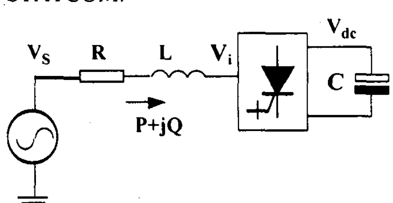

Fig.11 One-line Equivalent Circuit of STATCOM

Research indicates [15] that if the active losses are negligible, the reactance ratio determines the resonant characteristics of the STATCOM. In an actual STATCOM, the per-unit inductive reactance is normally chosen in the range between 0.15 and 0.25, then the preferred range of capacitance may be in the range between 50 and 150% of STATCOM rating depending on the inductance adapted. And if the reactance ratio satisfies the following relationship the harmonic components of ac current caused by nth component of input will be zero, this may be used to eliminate certain harmonic component.

The calculation results show that under unbalance operation, as the per-unit resistance increases such as in the case of FACTS device with small capacity, the resonance will be well damped. Simulation as well as physical experiment results validate above theory analysis. Hence the correct selection of passive parameters impose great influence on the performance, carefully select the capacitance and inductance is essential to effectively operation of FACTS.

3.6 Multi-Objective Control

The demands of the power system to FACTS and DFACTS controller are multi-objective. For example, the primary purpose of STATCOM application is to maintain bus voltage at or near a constant level. In addition, STATCOM is also used to improve transient stability by dynamically supporting the voltages at key points and steady state stability by helping to increase swing oscillation damping. However, the above functions demand different controls in nature.

Fig.12 gives an example of the effects of two types of STATCOM controller on the system response during a major disturbance. Obviously, a pure voltage control is quite effective in supporting the terminal voltage, but does not contribute significantly to system damping, and the pure damping control suppresses the oscillation quickly, but does little for supporting the system voltage either. Furthermore, these control demands may conflict to each other. For example, during a major disturbance, the bus voltage at the sending end needs to be somewhat relaxed (but no larger than 1.2 pu.) in order to increase the transient limitation to stabilize the system after the fault is cleaned. But, the voltage control function will offset its effect, and it may even amplify the oscillation and deteriorate the transient stability of the system. More than that, if the damping is over strong, the dynamic performance may be dull. To coordinate them is a very difficult work.

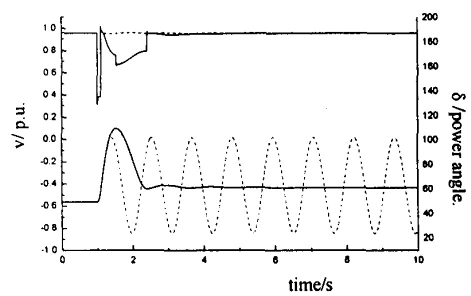

Fig.12 Comparison of Different Control Strategies
—— Pure Damping Control
- - - - Pure Voltage Control
Upper: Voltage Response,
Lower: Power Angle Oscillation

In order to cope with the above problems, a typical STATCOM controller, as shown in Fig.13, is usually comprised of a voltage controller (VC), and a power damping controller (PDC), whose damping signal is supplemented to the voltage control loop for damping system oscillation under major disturbance. However, the conventional design methods for STATCOM controllers are based on a linearized model. This implies the tuning of the controller is valid only in the neighborhoods of a specified operating point. As a nonlinear and variable structure system, if its operating point drifts from the specified condition as the result of continuous load changes or unpredictable major disturbances, the tuning of the controller may be not valid, and may lead to undesired and sustained oscillations in power and voltage. Furthermore, the maximum rating of the STATCOM limits the effectiveness of STATCOM on the power oscillation damping, and a time-optimal approach, i.e. bang-bang control is normally adapted in power oscillation damping. The discrete nature of such a control makes the control problem more complicated. In consideration of that fuzzy sets can provide a possibility to incorporate the continuos control with the discrete one, a fuzzy rule based hybrid controller may be a better solution.

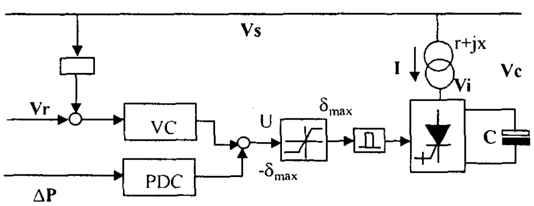

Fig.13 The STATCOM Controller

Besides, almost all the existing power systems are large area covered and interconnected systems. The geographic distance between the center point and the edge points is very far. It is difficult to get the current state information of a distant bus quickly by now. It results that the input signals of the controller must be local, otherwise it will be a long time delay and cause possible oscillation.

From above discussion, a good control strategy for FACTS should be independent of the accurate model of the power systems to some extent, intelligent and with self-learning ability which can adjust its control output according to the changing conditions of the power systems. Furthermore, the control strategy should be local input signals based in present. The Artificial Intelligent control strategies with self-learning ability such as Artificial Neural Network, Fuzzy Logic Sets and Iterative Learning Control are the optimal candidates.

4. Conclusion

The benefits of FACTS application have been successfully demonstrated in China as well as in the other parts of the world. This paper gives a short description of the research and development of FACTS and DFACTS technologies in China, and identifies some special theory and technology difficulties met in the development of FACTS inverter. The solution of above difficulties may speed up the development of FACTS and DFACTS technologies, and provide new possibilities and more flexibility to the existing system. Along with the fast development of China's economy, the reconstruction of China's urban and rural power network offers the best opportunity for the development and implementation of FACTS and DFACTS technologies, and for the researchers and engineers in the electrical engineering trade.

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