

POWER SYSTEM STABILITY ENHANCEMENT USING FACTS CONTROLLERS: A REVIEW

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الخلاصة:

يزداد الطلب على الطاقة الكهربائية يوماً بعد يوم مع محدودية التوسع في عمليتي التوليد والنقل للطاقة الكهربائية نظراً لمحدودية المصادر و الضغوط البيئية. ونتيجة لذلك فإن بعض خطوط النقل تعمل تحت زيادة الحمل مما يؤثر سلباً على اتزان واستقرار نظم القوى الكهربائية. وتعتبر أنظمة النقل المرنة (FACTS) من المجالات التي شهدت تطوراً سريعاً خلال السنوات القليلة الماضية لما لها من قدرة كبيرة على التحكم في أنظمة النقل الكهربائية، كما يزيد من قدرتها على نقل الطاقة الكهربائية مع عدم الإخلال بوثوقيتها. و تهدف هذه الورقة إلى تقديم مراجعة شاملة و متعمقة عن استخدام أنظمة النقل المرنة لتعزيز استقرار نظم القوى الكهربائية. كما تمت مناقشة العديد من الأمور المتعلقة بتركيب هذه الأنظمة و إدماجها في نظم القوى الكهربائية، و كذلك المقارنة بين أداء العديد منها. وتم أيضاً مناقشة الخبرات العملية لبعض شركات توليد الطاقة الكهربائية ونقلها و توزيعها، والتطور في مكونات هذه الأنظمة. كما تم أيضاً - باختصار - مناقشة التطبيقات المختلفة لهذه الأنظمة. وتشتمل هذه الورقة على تصنيف و مناقشة 227 بحثاً منشوراً.

ABSTRACT

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS controllers has been extensively investigated. This paper presents a comprehensive review on the research and developments in the power system stability enhancement using FACTS damping controllers. Several technical issues related to FACTS installations have been highlighted and performance comparison of different FACTS controllers has been discussed. In addition, some of the utility experience, real-world installations, and semiconductor technology development have been reviewed and summarized. Applications of FACTS to other power system studies have also been discussed. About two hundred twenty seven research publications have been classified and appended for a quick reference.

Key words: power system stability, PSS, FACTS, SVC, TCSC, TCPS, STATCOM, SSSC, UPFC, IPFC

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Paper Received 13 November 2007; Accepted 12 November 2008

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1. INTRODUCTION

Since the development of interconnection of large electric power systems, there have been spontaneous system oscillations at very low frequencies in order of 0.2–3.0 Hz. Once started, they would continue for a long period of time. In some cases, they continue to grow causing system separation due to the lack of damping of the mechanical modes [1; 2].

In the past three decades, power system stabilizers (PSSs) have been extensively used to increase the system damping for low frequency oscillations. The power utilities worldwide are currently implementing PSSs as effective excitation controllers to enhance the system stability [1–12]. However, there have been problems experienced with PSSs over the years of operation. Some of these were due to the limited capability of PSS, in damping only local and not interarea modes of oscillations. In addition, PSSs can cause great variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing system stability [13]. This situation has necessitated a review of the traditional power system concepts and practices to achieve a larger stability margin, greater operating flexibility, and better utilization of existing power systems.

Flexible AC transmission systems (FACTS) have gained a great interest during the last few years, due to recent advances in power electronics. FACTS devices have been mainly used for solving various power system steady state control problems such as voltage regulation, power flow control, and transfer capability enhancement. As supplementary functions, damping the interarea modes and enhancing power system stability using FACTS controllers have been extensively studied and investigated. Generally, it is not cost-effective to install FACTS devices for the sole purpose of power system stability enhancement.

In this work, the current status of power system stability enhancement using FACTS controllers was discussed and reviewed. This paper is organized as follows. The development and research interest of FACTS is presented in Section 2. Section 3 discusses the potential of the first generation of FACTS devices to enhance the low frequency stability while the potential of the second generation is discussed in Section 4. Section 5 highlights some important issues in FACTS installations such as location, feedback signals, coordination among different control schemes, and performance comparison. Major real-world installations and recent developments in power electronic devices used in FACTS controllers have been summarized in Section 6. Applications of FACTS to optimal power flow and deregulated electricity market as steady state problems have been discussed in Section 7. Some concluding remarks are highlighted in Section 8. About two hundred research publications are reviewed, discussed, classified, and appended for a quick reference.

2. FACTS DEVICES

2.1. Overview

In the late 1980s, the Electric Power Research Institute (EPRI) formulated the vision of the Flexible AC Transmission Systems (FACTS) in which various power-electronics based controllers regulate power flow and transmission voltage and mitigate dynamic disturbances. Generally, the main objectives of FACTS are to increase the useable transmission capacity of lines and control power flow over designated transmission routes. Hingorani and Gyugyi [14] and Hingorani [15; 17] proposed the concept of FACTS. Edris *et al.* [18] proposed terms and definitions for different FACTS controllers.

There are two generations for realization of power electronics-based FACTS controllers: the first generation employs conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers, the second generation employs gate turn-off (GTO) thyristor-switched converters as voltage source converters (VSCs). The first generation has resulted in the Static Var Compensator (SVC), the Thyristor- Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS) [19; 20]. The second generation has produced the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC) [21–24]. The two groups of FACTS controllers have distinctly different operating and performance characteristics.

The thyristor-controlled group employs capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the on and off periods of the fixed capacitor and reactor banks and thereby realize a variable reactive impedance. Except for losses, they cannot exchange real power with the system.

The voltage source converter (VSC) type FACTS controller group employs self-commutated DC to AC converters, using GTO thyristors, which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of capacitor or reactor banks. The converter with energy storage device can also exchange real power with the system, in addition to the independently controllable reactive power. The VSC can be used uniformly to control transmission line voltage, impedance, and angle by providing reactive shunt compensation, series compensation, and phase shifting, or to control directly the real and reactive power flow in the line [24].

2.1. Interest Measure for FACTS

For the purpose of this review, a literature survey has been carried out including two of the most important and common databases, namely, the IEEE/IEE electronic library and ScienceDirect electronic databases. The survey spans over the last 15 years from 1990 to 2004. For convenience, this period has been divided to three sub-periods; 1990–1994, 1995–1999, and 2000–2004. The number of publications discussing FACTS applications to different power system studies has been recorded. The results of the survey are shown in Figure 1. It is clear that the applications of FACTS to different power system studies have been drastically increased in last five years. This observation is more pronounced with the second generation devices as the interest is almost tripled. This shows more interest for the VSC-based FACTS applications. The results also show a decreasing interest in TCPS while the interest in SVC and TCSC slightly increase.

Generally, both generations of FACTS have been applied to different areas in power system studies including optimal power flow [25–29], economic power dispatch [30], voltage stability [31; 32], power system security [33], and power quality [34–35].

Applications of FACTS to power system stability in particular have been carried out using same databases. The results of this survey are shown in Figure 2. It was found that the ratio of FACTS applications to the stability study with respect to other power system studies is more than 60% in general. This reflects clearly the increasing interest to the different FACTS controllers as potential solutions for power system stability enhancement problem. It is also clear that the interest in the 2nd generation of FACTS has been drastically increased while the interest in the 1st generation was decreased.

The potential of FACTS controllers to enhance power system stability has been discussed by Noorozian and Anderson [36], where a comprehensive analysis of damping of power system electromechanical oscillations using FACTS was presented. Wang and Swift [37] have discussed the damping torque contributed by FACTS devices, where several important points have been analyzed and confirmed through simulations.

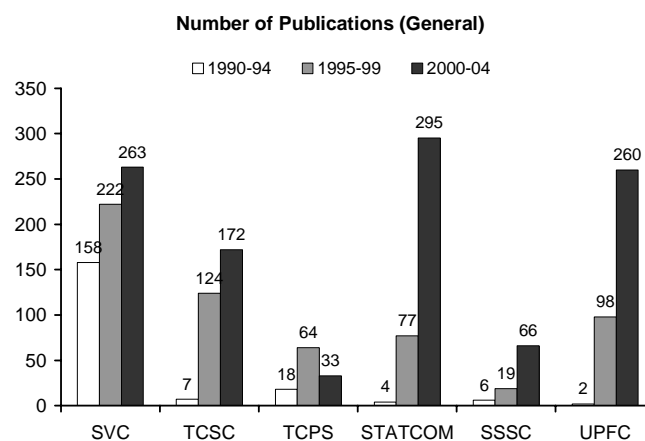


Figure 1. Statistics for FACTS applications to different power system studies

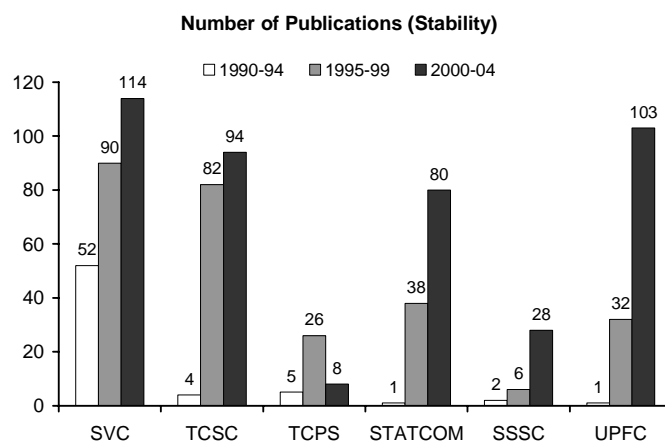


Figure 2. Statistics for FACTS applications to power system stability

3. FIRST GENERATION OF FACTS

3.1. Static VAR Compensator (SVC)

It is known that the SVCs with an auxiliary injection of a suitable signal can considerably improve the dynamic stability performance of a power system [38–61]. In the literature, SVCs have been applied successfully to improve the transient stability of a synchronous machine [38]. Hammad [39] presented a fundamental analysis of the application of SVC for enhancing the power systems stability. Then, the low frequency oscillation damping enhancement via SVC has been analyzed [40–46]. It is shown that the SVC enhances the system damping of local as well as interarea oscillation modes. Self-tuning and model reference adaptive stabilizers for SVC control have been also proposed and designed [47–49]. Robust SVC controllers based on H_∞ , structured singular value μ , and quantitative feedback theory QFT have been presented to enhance system damping [50; 51]. However, the importance and difficulties in the selection of weighting functions of H_∞ optimization problem have been reported. In addition, the additive and/or multiplicative uncertainty representation can not treat situations where a nominal stable system becomes unstable after being perturbed [52]. Moreover, the pole-zero cancellation phenomenon associated with this approach produces closed loop poles whose damping is directly dependent on the open loop system (nominal system) [53]. Genetic algorithms and fuzzy logic based approaches have been proposed for SVC control [54–60]. The superiority of these approaches over the conventional methods is confirmed through time domain simulations. Messina and Barocio [61] studied the nonlinear modal interaction in stressed power systems with multiple SVC voltage support. It was observed that SVC controls can significantly influence nonlinear system behavior especially under high-stress operating conditions and increased SVC gains.

3.2. Thyristor-Controlled Series Capacitor (TCSC)

Many different techniques have been reported in the literature pertaining to investigating the effect of TCSC on power system stability [62–72]. Several approaches based on modern control theory have been applied to TCSC controller design. Chen *et al.* [62] presented a state feedback controller for TCSC by using a pole placement technique. However, the controller requires all system states which reduces its applicability. Chang and Chow [63] developed a time optimal control strategy for the TCSC where a performance index of time was minimized. A fuzzy logic controller for a TCSC was proposed in [64]. The impedance of the TCSC was adjusted based on machine rotor angle and the magnitude of the speed deviation. In addition, different control schemes for a TCSC were proposed such as variable structure controller [65; 66], bilinear generalized predictive controller [67], and H_∞ -based controller [68]. The neural networks [69; 70] have been proposed for TCSC-based stabilizer design. The parameters of the stabilizers are determined by genetic algorithm (GA) [70]. The damping characteristics of the designed stabilizers have been demonstrated through simulation results on a multimachine power system. Wang *et al.* [71] presented a robust nonlinear coordinated control approach to excitation and TCSC for transient stability enhancement. The excitation controller and TCSC controller have been designed separately using a direct feedback linearization technique. Lee and Moon [72] presented a hybrid linearization method in which the algebraic and the numerical linearization technique were combined.

3.3. Thyristor-Controlled Phase Shifter (TCPS)

A considerable attention has been directed to realization of various TCPS schemes [73,74]. However, a relatively little work in TCPS control aspects has been reported in the literature. Baker *et al.* [75] developed a control algorithm for TCPS using stochastic optimal control theory. Edris [76] proposed a simple control algorithm based on

the equal area criterion. Jiang *et al.* [77] proposed a TCPS control technique based on nonlinear variable structure control theory. In their control scheme the phase shift angle is determined as a nonlinear function of rotor angle and speed. However, in real-life power system with a large number of generators, the rotor angle of a single generator measured with respect to the system reference will not be very meaningful. Tan and Wang [78] proposed a direct feedback linearization technique to linearize and decouple the power system model to design the excitation and TCPS controllers.

4. SECOND GENERATION OF FACTS

4.1. Static Compensator (STATCOM)

The emergence of FACTS devices and in particular GTO thyristor-based STATCOM has enabled such technology to be proposed as serious competitive alternatives to conventional SVC [79]. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system.

The effectiveness of the STATCOM to control the power system voltage was presented in [80]. However, the effectiveness of the STATCOM to enhance the angle stability has not been addressed. Abido [81] presented a singular value decomposition (SVD) based approach to assess and measure the controllability of the poorly damped electromechanical modes by STATCOM different control channels. It was observed that the electromechanical modes are more controllable via phase modulation channel. It was also concluded that the STATCOM-based damping stabilizers extend the critical clearing time and enhance greatly the power system transient stability. Haque [82] demonstrated by the use of energy function [82] the capability of the STATCOM to provide additional damping to the low frequency oscillations.

The STATCOM damping characteristics have been also analyzed and addressed [83–91] where different approaches to STATCOM-based damping controller design have been adopted such as loop-shaping [86], pole-placement [87], multivariable feedback linearization [88; 89], H_∞ control [90], and intelligent control [91].

4.2. Static Synchronous Series Compensator (SSSC)

The SSSC has been applied to different power system studies to improve the system performance [92–98]. There has been some work done to utilize the characteristics of the SSSC to enhance power system stability [99; 100]. Wang [99] investigated the damping control function of an SSSC installed in power systems. The linearized model of the SSSC integrated into power systems was established and methods to design the SSSC damping controller were proposed. Kumkratug and Haque [100] demonstrated the capability of the SSSC to control the line flow and to improve the power system stability. A control strategy of an SSSC to enlarge the stability region has been derived using the direct method. The effectiveness of the SSSC to extend the critical clearing time has been confirmed through simulation results on a single machine infinite bus system.

4.3. Unified Power Flow Controller (UPFC)

A unified power flow controller (UPFC) is the most promising device in the FACTS concept. It has the ability to adjust the three control parameters, *i.e.* the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently. A UPFC performs this through the control of the in-phase voltage, quadrature voltage, and shunt compensation.

Makombe and Jenkins [101] experimentally proved that a UPFC can control the three control parameters either individually or in appropriate combinations at its series-connected output while maintaining reactive power support at its shunt-connected input. Limyingcharoen *et al.* [102] investigated the mechanism of the three control methods of a UPFC in enhancing power system damping. It was shown that a significant reduction in the transient swing can be obtained by using a simple proportional feedback of machine rotor angle deviation. Fujita *et al.* [103] investigated the high frequency power fluctuations induced by a UPFC.

Several trials have been reported in the literature to model a UPFC for steady-state and transient studies. Under the assumption that the power system is symmetrical and operates under three-phase balanced conditions, Nabavi-Niaki and Iravani [104] developed a steady-state model, a small-signal linearized dynamic model, and a state-space large-signal model of a UPFC. Wang [105; 106] developed two UPFC models which have been linearized and incorporated into the Phillips–Heffron model. It was observed that, unless the UPFC is equipped with a damping controller, the voltage control of the DC link capacitor may interact negatively with PSSs installed in the power system [106]. A current injected UPFC model for improving power system dynamic performance was developed by Meng and So [107] where a UPFC was represented by an equivalent circuit with a shunt current source and a series voltage source. The presented model features the symmetry property of the Y_{bus} matrix.

It is generally accepted that the addition of a supplementary controller to the UPFC can significantly enhance power system damping. Hence, a number of control schemes have been suggested to perform the oscillation damping task. Huang *et al.* [108] attempted to design a conventional fixed-parameter lead-lag controller for a UPFC installed in the tie-line of a two-area system to damp the interarea mode of oscillation. Robust control schemes using H_∞ control have also been introduced [109–110]. A multi-input–multi–output (MIMO) PI controller has been proposed in [111]. It has been illustrated that if more than one UPFC controller, such as a power flow controller, an AC voltage controller, and a DC voltage controller, were designed separately, the dynamic interactions among the various control channels may have a detrimental effect on the system stability. A nonlinear control strategy for phase angle of the series branch of a UPFC and linear control strategies for the other channels have been hybridized for stability enhancement of a multimachine system [112]. The adverse effect of DC voltage regulator on the damping characteristics of UPFC has been addressed in [113]. In addition, different control channels of the UPFC have been evaluated using a controllability index.

Mishra *et al.* [114–117] developed different intelligent damping controllers for a UPFC to damp both local and interarea modes of oscillation for a multimachine system. The effectiveness of such controllers has been demonstrated and reported with satisfactory success.

5. FACTS INSTALLATION ISSUES

For the maximum effectiveness of the controllers, the selection of installing locations and feedback signals of FACTS-based stabilizers must be investigated. On the other hand, the robustness of the stabilizers to the variations of power system operation conditions is equally important factor to be considered. Also, the coordination among different stabilizers is a vital issue to avoid the adverse effects. Additionally, performance comparison is an important factor that helps in selection of a specific FACTS device.

5.1. Location and Feedback Signals

Generally, the location of FACTS devices depends on the objective of the installation. The optimal location can be governed by increasing system loadability [118–120], minimizing the total generation cost [121], and enhancing voltage stability [122].

Wang *et al.* [123] presented two indices for selecting the optimal location of PSSs or FACTS-based stabilizers. The first index was based on the residue method while the second index was based on damping torque analysis. This work has been further developed in [124] where a new method independent of the eigensolution to identify the optimal locations and feedback signals of FACTS-based stabilizers was proposed. The new method avoids difficulty of eigensolution and reduces the computation cost. Yang *et al.* [125] applied the residue method to the linearized power system model to determine the location and the feedback signal of TCSC in a multimachine power system. It was concluded that the tie line power signal is more effective than the speed difference as the input of TCSC and enhances greatly the damping characteristics of TCSC. Kulkarni and Padiyar [126] proposed a location index based on circuit analogy for the series FACTS controllers. The feedback signals used were synthesized using local measurements. The method is validated on two different multimachine power systems and very important comments have been highlighted in this work. Rosso *et al.* [127] presented a detailed analysis of TCSC control performance for improving system stability with different input signals. Namely, the line active power and the line current magnitude were considered. The simulation results demonstrated that the TCSC damping capability is more effective with line current input signal. Farsangi *et al.* [128] presented the minimum singular value, the right half plane zeros, the relative gain array, and the Hankel singular values as indicators to find the stabilizing signals of FACTS devices for damping interarea oscillations. Different input–output controllability analyses were used to assess the most appropriate input signals for SVC, SSSC, and UPFC. Ramirez and Coronado [129] presented a technique based on the frequency response to select the best location of FACTS devices and the best input control signal in order to get the major impact on the damping of electromechanical modes of concern. Chaudhuri *et al.* [130; 131] demonstrated that the use of global stabilizing signals for effective damping of multiple swing modes through single FACTS device is one of the potential options worth exploring. Fan *et al.* [132] presented two residue-based indices to identify an effective local signal that can be used by a TCSC as a supplementary controller to dampen interarea oscillations for multiple power system operating conditions. The first index is to identify the most effective signal to feedback for different operating points and the second index is to assess the interaction of the controller with other oscillation modes.

5.2. Coordination among Different Control Schemes

Mahran *et al.* [133] presented a coordinated PSS and SVC controller for a synchronous generator. However, the proposed approach uses recursive least squares identification which reduces its effectiveness for on-line applications. Various approaches for coordinated design of PSS and SVC are also presented in [134–136]. The coordinated design of several TCSCs [137–139], several SVCs [140,141], TCSC and SVC [142–144], HVDC and SVC [145], and PSS

and different FACTS stabilizers [146–150] has been discussed. Hiyama *et al.* [151] presented a coordinated fuzzy logic-based scheme for PSS and switched series capacitor modules to enhance overall power system stability. Wang [152] have discussed the issue of selection of typical operating conditions for robust design of multiple stabilizers in coordinated manner to damp multimode oscillations in multimachine power systems. In other work, Wang and Swift [153; 154] presented a phase compensation based approach to coordinated setting of TCSC-based stabilizer and PSS. The results were promising and encourage further research in this direction. However, all controllers were assumed proportional and no efforts have been done towards the controller design. Abido and Abdel-Magid [155–157] presented coordinated design of control schemes for the excitation and different FACTS controllers. Several operating conditions and parameter uncertainties have been considered in the design process of different stabilizers to ensure the robustness over a wide range of operating conditions.

The coordination between the AC and DC voltage PI controllers of the STATCOM was investigated using a multivariable design approach [158]. However, the structural complexity of the presented multivariable PI controllers with different channels reduces their applicability. Ramirez *et al.* [159] presented a technique to design and coordinate PSSs and STATCOM-based stabilizers to enhance the system stability and avoid the adverse interaction among stabilizers. Ramirez *et al.* [160] extended the work to coordinate among three different types of stabilizers, namely, PSSs, TCSC, and UPFC. The results exhibit a meritorious performance of the coordinated stabilizers. A systematic approach to establish the dynamic model of a multimachine power system installed with multiple SVCs, TCSCs, TCPSs, STATCOMs, and UPFCs was presented [161]. The adverse interactions among these stabilizers, which may lead to the loss of the system stability, has been examined.

Control systems for FACTS controllers may have to be designed by using intelligent, adaptive digital controllers based on information obtained from wide-area measurement networks. For systems using FACTS controllers, aiming for high levels of damping may not be a safe design goal for wide-area control. Adequate damping over the largest realistic range of operating conditions may be a more desirable criterion to fulfill [162]. The coordination of multiple FACTS controllers in the same system as well as in the adjacent systems must be investigated extensively and implemented to ensure the security of power-system operation.

5.3. Performance Comparison

The relative efficacy of different FACTS controllers in enhancing of power system stability is investigated [163–167]. The capabilities of PSS, SVC-based stabilizer, TCSC-based stabilizer, and TCPS-based stabilizer to control the electromechanical mode over wide range of operating conditions were discussed in [168] for a weakly connected power system. The results show that the controllability of the electromechanical mode with the TCPS is relatively higher especially at low loading levels and the electromechanical mode is most controllable by TCSC at heavy loading.

Similar studies have been carried out for a PSS and different STATCOM and UPFC control channels [81, 169]. Nelson *et al.* [170] considered four FACTS controllers to be evaluated and compared: the SVC, the STATCOM, the TCSC, and the UPFC. The effects of different controllers are expressed in terms of the critical clearing time (CCT). The controller parameters are selected with only consideration of maximizing the CCT. The CCT obtained for the different controllers are compared. Among the shunt controllers, the STATCOM performs better than SVC. The TCSC is more effective than the shunt controllers, as it offers greater controllability of the power flow in the line. The UPFC is by far the best controller, as it provides independent control over the bus voltage and the line real and reactive power flows.

6. FACTS TECHNOLOGY IMPLEMENTATION AND DEVELOPMENT

6.1. FACTS Installations and Utility Experience

In the emerging deregulated power systems, FACTS controllers will provide several benefits at existing or enhanced levels of reliability such as balancing the power flow in parallel networks over a wide range of operating conditions, alleviating unwanted loop flow, mitigating interarea power oscillations, and enhancing the power-transfer capacity of existing transmission corridors [171].

In addition to the several successful installations of the first generation, the second generation of FACTS controllers which uses GTO-based VSC configurations is expected to evolve into another mature family of FACTS controllers as several power utilities worldwide have started installing such controllers. In 1991, a ± 80 MVAR STATCOM developed by Kansai Electric Power Co. (KEPCO) and Mitsubishi Motors was installed at Inuyama Switching Station to improve the stability of a 154 kV system [172]. In 1995, a ± 100 MVAR STATCOM was commissioned for the Tennessee Valley Authority (TVA) [173–175]. The TVA STATCOM is the first of its kind, using GTO thyristor valves, to be commissioned in United States. In 1997, American Electric Power (AEP) has selected its Inez substation in eastern Kentucky for the location of the world's first UPFC installation [176; 177]. The

UPFC is comprised of two ± 160 MVA GTO thyristor-based inverters, this installation is the highest power GTO-based FACTS device ever installed. EPRI and Siemens also developed a ± 200 MVAR convertible static compensator (CSC), which was installed at Marcy 345 kV substation in 2001 to provide strong dynamic voltage support and to control the power flow. Depending on the transmission control need, the installed CSC can provide four control modes where it can be controlled to operate as STATCOM, SSSC, UPFC, and IPFC [178]. A ± 75 MVAR STATCOM developed by ALSTOM, the first cascade multilevel-inverter-based STATCOM in the world, entered commercial service at NGC (National Grid Company) East Claydon, England in 2001 [179]. A $+133/-41$ MVAR STATCOM system has been installed at the Vermont Electric Power Company's Essex 115 kV substation since May 2001, to compensate for heavy increases in summertime electric usage [180]. A three-level ± 100 MVAR STATCOM is installed by San Diego Gas & Electric (SDG&E) at Talega substation, California in October 2002, and is to be extended to a Back-To-Back system [181]. ABB has installed six STATCOM systems (also named SVC Light) since 1997; two installations in USA and one installation in Sweden, Germany, Finland, and France [182]. A ± 250 kVAR prototype D-STATCOM was designed and installed for the first time [183]. More FACTS installations to improve the performance of different power system utilities can be found in [184].

6.2. FACTS Devices Technology Development

The technology behind thyristor-based FACTS controllers has been present for several decades and is therefore considered mature. More utilities are likely to adopt this technology in the future as more promising GTO-based FACTS technology is fast emerging. Recent advances in silicon power-switching devices that significantly increase their power ratings will contribute even further to the growth of FACTS technology. A relatively new device called the Insulated Gate Bipolar Transistor (IGBT) has been developed with small gate consumption and small turn-on and turn-off times. The IGBT has bi-directional current carrying capabilities. More effective use of pulse width modulation techniques for control of output magnitude and harmonic distortion can be achieved by increasing the switching frequencies to the low kHz range. However, IGBT has until recently been restricted to voltages and currents in the medium power range. Larger devices are now becoming available with typical ratings on the market being 3.3 kV/1.2 kA (Eupec), 4.5 kV/2 kA (Fuji), and 5.2 kV/2 kA (ABB) [185; 186].

The Integrated Gate Commutated thyristor (IGCT) combines the excellent forward characteristics of the thyristor and the switching performance of a bipolar transistor. In addition, IGCT does not require snubber circuits and it has better turn-off characteristics, lower conducting and switching loss, and simpler gate control compared with GTO and IGBT [182]. The ratings of IGCT reach 5.5 kV/1.8 kA for reverse conducting IGCTs and 4.5 kV/4 kA for asymmetrical IGCTs [187]. Currently, typical ratings of IGCTs on the market are 5.5 kV/2.3 kA (ABB) and 6 kV/6 kA (Mitsubishi) [185].

Injection Enhanced Gate Transistor (IEGT) is a newly developed MOS device that does not require snubber circuits and it has smaller gate power and higher turn-on and turn-off capacity compared with GTO [182]. The ratings of IEGT are in the order of 4.5 kV/1.5 kA [188].

Based on integration of the GTO and the power MOSFET, the Emitter Turn-Off (ETO) thyristor is presented as a promising semiconductor device for high switching frequency and high power operation. The ETO has 5 kA snubberless turn off capability and much faster switching speed than that of GTO [189]. A modular ETO-based 1.5 MVA H-bridge converter is used to build a cascaded-multilevel converter for high power FACTS devices [190,191].

A novel approach to distributed FACTS controllers based on active variable inductance has been recently proposed to realize cost-effective power flow control [192]. The power flow control using distributed FACTS controllers can be achieved by introducing a distributed series impedance concept which can be further extended to realize a distributed static series compensator [193].

7. FACTS APPLICATIONS TO STEADY STATE POWER SYSTEM PROBLEMS

For the sake of completeness of this review, a brief overview of the FACTS devices applications to different steady state power system problems is presented in this section. Specifically, applications of FACTS in optimal power flow and deregulated electricity market will be reviewed.

7.1. FACTS Applications to Optimal Power Flow

In the last two decades, researchers developed new algorithms for solving the optimal power flow problem incorporating various FACTS devices [194]. Generally in power flow studies, the thyristor-controlled FACTS devices, such as SVC and TCSC, are usually modeled as controllable impedance [14, 24, 36, 195–197]. However, VSC-based FACTS devices, including IPFC and SSSC, shunt devices like STATCOM, and combined devices like UPFC, are more complex and usually modeled as controllable sources [14, 24, 104, 196–200]. Padhy *et al.* [201] have presented a new hybrid model for OPF incorporating FACTS devices to overcome the classical optimal power flow algorithm where load demands, generation outputs, and cost of generation are treated as fuzzy variables.

Chung and Li [202] presented an improved genetic algorithm (GA) to solve OPF problems in power system with FACTS where TCPS and TCSC are used to control power flow. In the solution process, GA coupled with full AC power flow, selects the best regulation to minimize the total generation fuel cost and keep the power flows within their secure limits. Shao and Vittal [203] presented a linear programming (LP)—based OPF algorithm for corrective FACTS control to relieve overloads and voltage violations caused by system contingencies. The optimization objective was chosen to minimize the average loadability on highly loaded transmission lines. The algorithm is implemented with MATLAB and tested on the New England 39-bus system and the WECC 179-bus system.

Ye and Kazerani [204] derived analytically the relationship between the series voltage injected by the UPFC/IPFC and the resulting power flow in the transmission line. This relationship was used to design two power flow control schemes that are applicable to any series-connected FACTS controller with the capability of producing a controllable voltage. The presented power flow control schemes were applied to a voltage-sourced converter-based IPFC, and the resulting control performances were examined using PSCAD/EMTDC simulation package.

7.2. FACTS Applications to Deregulated Electricity Market

Nowadays, electricity demand is rapidly increasing without major reinforcement projects to enhance power transmission networks. Also, the electricity market is going toward open market and deregulation creating an environment for forces of competition and bargaining. Electricity utilities are in need to serve more loads through their networks and also maintain the system security. FACTS devices can be an alternative to reduce the flows in heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network, reduced cost of production, and fulfilled contractual requirements by controlling the power flows in the network. Generally, the changing nature of the electricity supply industry is introducing many new subjects into power system operation related to trading in a deregulated competitive market. Commercial pressures on obtaining greater returns from existing assets suggests an increasingly important role for dynamic network management using FACTS devices and energy storage as an important resource in generation, transmission, distribution, and customer service. The roles and influences of FACTS devices on deregulated electric power systems and their technical and economical benefits have been discussed in [205].

There has been an increased use of the FACTS devices applications in an electricity market having pool and contractual dispatches. FACTS impact has been investigated for reducing the production cost and transmission cost and solving loop flow problems [206–208]. The optimal location, type, and rating of FACTS installations has been discussed with the objective of economic generation allocation and dispatch in deregulated electricity market [209]. The optimal placement of a series-connected FACTS device to increase the maximum megawatt power transfer has been discussed and identified [210].

The problem of transmission congestion management and pricing has been identified as one of the critical and important tasks of the independent system operator (ISO) for the smooth functioning of competitive electricity markets [211–214]. Generally, congestion management can impose a barrier to the electricity trading and may prevent the existence of new contracts, lead to additional outages, increase the electricity prices in some regions of the electricity markets, and threaten system security and reliability [215–218]. A comprehensive bibliographical survey of the literature on transmission congestion management and the related issues has been reported [219] where several citations and sites dealing with the issue of congestion management are also listed.

8. CONCLUSIONS

In this review, the current status of power system stability enhancement using FACTS controllers was discussed and scrutinized. The essential features of FACTS controllers and their potential to enhance system stability was addressed. The location and feedback signals used for design of FACTS-based damping controllers were discussed. The coordination problem among different control schemes was also considered. Performance comparison of different FACTS controllers has been reviewed. The likely future direction of FACTS technology, especially in restructured power systems, was discussed as well. In addition, utility experience and major real-world installations and semiconductor technology development have been summarized. A brief review of FACTS applications to optimal power flow and deregulated electricity market has been presented. About two hundred twenty seven research publications have been classified, discussed, and appended for a quick reference. For the readers' convenience and broad spectrum, different applications of the first and second generations of FACTS devices over the last two decades can be reviewed through the annotated bibliographies [220–227].

ACKNOWLEDGEMENT

The author acknowledges the support and encouragement of King Fahd University of Petroleum & Minerals.

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