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A Survey on Flexible AC Transmission Systems (FACTS)

***Abstract**. The flexible alternating current transmission system (FACTS), a new technology based on power electronics, proposes an opportunity to improve controllability, stability, and power transfer capability of AC transmission systems. This article presents a comprehensive review and evaluation of FACTS controllers. This paper provides an extensive analysis on the research and improvements in the power system stability development using FACTS controllers. Several technical publications related to FACTS installations have been highlighted and performance comparison of different FACTS controllers has been discussed. Moreover, some of the utility experience, real-world installations, and semiconductor technology development have been outlined.*

***Streszczenie.** FACTS (elastyczny system transmisji prądu przemiennego) jest nową technologią bazującą na urządzeniach energoelektronicznych umożliwiającą poprawę sterowalności, stabilności i możliwości przesyłu energii. Artykuł prezentuje przegląd i ocenę kontrolerów stosowanych w tym systemie. Szczególny nacisk położono na porównanie parametrów. (**Analiza urządzeń systemu FACTS**)*

Keywords: Flexible AC Transmission System, TCPS, TCSC, SVC, STATCOM, SSSC, UPFC, IPFC.
Słowa kluczowe: FACTS, STATCOM, TSPS.

1. Introduction

Most of the problems are associated with the low frequency oscillation in interconnected power systems, especially in the deregulated paradigm. Small magnitude and low frequency oscillation often remained for a long time. To provide fast damping for the system and thus improve the dynamic performance, a supplementary control signal in the excitation system and/or the governor system of a generating unit can be used. As the most cost effective damping controller, power system stabilizer (PSS) has been widely applied to suppress the low frequency oscillation and enhance the system dynamic stability. PSSs contribute in maintaining reliable performance of the power system stability by providing an auxiliary signal to the excitation system. Application of PSSs has become the first measure to enhance the system damping. In the past two decades, the conventional power system stabilizer, i.e. a fixed parameters lead–lag compensator, is widely used by power system utilities. PSSs have been applied to provide the point of improvement of low frequency oscillations damping. However, PSSs may harmfully impact voltage profile, may effect in leading power factor, and may not be able to hold back oscillations resultant from difficult instability, particularly those three-phase faults which may happen at the generator terminals. So far, most main electric power system plants are equipped with PSS in many countries [1-5]. In some cases, if the use of PSS cannot provide sufficient damping for inter-area power swing, Flexible AC transmission systems devices (FACTS) damping controllers are alternative effective solutions [6-7]. The recent advances in power electronics have led to the development of the FACTS. FACTS devices are one of the recent propositions to alleviate such situations by controlling the power flow along the transmission lines and improving power oscillations damping. The use of these controllers increases the flexibility of the operation by providing more options to the power system operators. FACTS are designed to overcome the limitations of the present mechanically controlled power systems and enhance power system stability by using reliable and high-speed electronic devices. Generally, the FACTS devices are placed in power system to provide fast continuous control of power flow in the transmission system by controlling voltages at critical buses, by changing the impedance of transmission lines, or by controlling the phase angles between the ends of transmission lines. This paper provides a comprehensive review and evaluation of FACTS controllers. The literature shows an increasing interest in this topic for the last two decades, where the enhancement of system stability using FACTS controllers has been widely investigated. This paper provides an extensive analysis on the research and improvements in the power system stability development using FACTS controllers. Several technical publications related to FACTS installations have been highlighted and performance comparison of different FACTS controllers has been discussed. Moreover, some of the utility experience, real-world installations, and semiconductor technology development have been outlined. For the aim of this review, a literature overview has been carried out including Scopus databases which are the largest abstract and citation databases of research literature and quality web sources. The survey spans over the last 16 years from 1995 to 2011. Fig. 1 statistically illustrates the number of published research papers on the subject of the FACTS problem during the last 16 years.

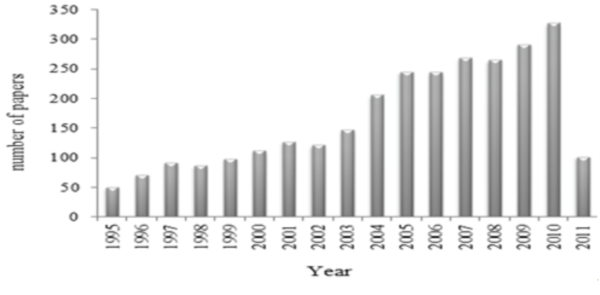

Fig.1. Number of papers published in each year on the subject of FACTS

2. Flexible AC Transmission System (FACTS)

In spite of the interesting properties provided by PSSs to enhance power system damping, they have adverse effect on system voltage profile, may result in leading power factor operation, and may not be able to maintain system stability, especially following a large fault occurring close to the generator terminal [8]. This theory and improvements in the power electronics area led to a new advance introduced by the Electric Power Research Institute in the late 1980 and named FACTS. It was an answer for a more efficient use of already existing resources in present power systems while maintaining and even improving power system security. In [9], the author introduced this new concept, initiating a new direction in power system research. In 1988, Hingorani [10] have initiated the concept of FACTS devices and their application. Edris et al. [11] proposed terms and definitions for different FACTS controllers. There are two groups for recognition of power electronics-based FACTS controllers: the first group occupies conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers, the second group occupies gate turn-off (GTO) thyristor-switched converters as voltage source converters (VSCs). The first group has produced in the Thyristor- Controlled Series Capacitor (TCSC), the Static VAR Compensator (SVC), and the Thyristor-Controlled Phase Shifter (TCPS). The second group has produced in the Unified Power Flow Controller (UPFC), the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC) and the Interline Power Flow Controller (IPFC). For the aim of this review, a literature overview has been carried out including the Scopus databases that is the largest abstract and citation database of research literature and quality web sources. The survey spans over the last 15 years from 1995 to 2010. This period has been divided to three sub-periods; 1995–2000, 2001–2006, and 2007–2011.

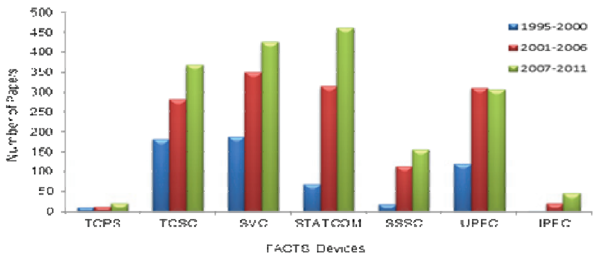

Fig.2. Statistics for FACTS applications to different power system studies

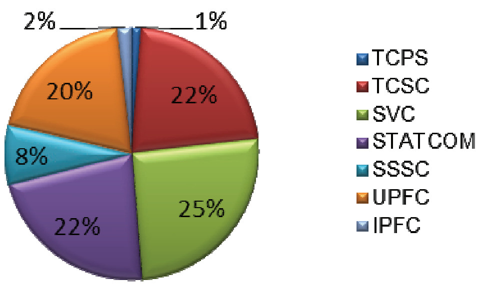

Fig.3. Pie chart showing the publication distribution of FACTS devices

The number of publications discussing FACTS applications to different power system studies has been recorded and Fig. 2 shows the results of the survey. Also Fig. 3 shows the distribution of publications for FACTS devices in 16 years.The results indicate significantly increasing in STATCOM and UPFC 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 damping of oscillation in power system, optimal power flow, economic power dispatch, voltage stability, power system security and power quality. Applications of FACTS to power system stability in particular have been carried out using same databases. Noorozian and Anderson [12] presented the ability of FACTS controllers to increase power system stability. In [13] was considered the damping torque contributed by FACTS devices, where some main aims have been analyzed and proved through simulations.

3. First Generation of FACTS Devices

3.1 Thyristor Controlled Phase Shifters (TCPS)

The TCPS is one of the potential options of recently proposed FACTS devices. Researchers have developed different TCPS schemes in the literature [14-28]. Ise *et al.* [14] compared between two different TCPS schemes. Compared with other FACTS devices, little attention have been paid to TCPS modeling and control. The TCPS control problem has been investigated using linear control techniques [14-15]. A scheme was used in [15] to study the stabilizing effect of TCPSs on inter-area modes of oscillations. In [16] was presented simulated annealing (SA) algorithm to determine the optimum settings of TCPS lead-lag controller parameters. Moreover, nonlinear TCPS control schemes have been investigated in [17-22]. Wang [20-22] proposed a new method to TCPS. These papers were proposed a nonlinear coordinated generator excitation and TCPS controller to enhance the transient stability of a power system. However, because of its difficulties, a little research has been devoted to the problem of modeling of a TCPS applied for a multi-machine system [23-24]. The TCPS was modelled in [23] as node power injections whose effects appear as additional bus power injections at internal buses of the generator. Another mathematical model was reported by Ngan [24] for a Type-B TCPS. In [25] was presented a best optimal location of TCPS by using congestion management in normal and contingency conditions. A TCPS in series with the tie-line was presented in [26] that it was possible to damp the system frequency and tie-power oscillations by controlling the phase angle of TCPS. Furthermore, the TCPS was considered for the damping of power swings [27]. In [28] was presented the analysis of automatic generation control of a two-area interconnected TCPS based hydrothermal system in the continuous mode using a fuzzy logic controller under open market scenario.

3.2 Thyristor- Controlled Series Capacitor (TCSC)

Many various techniques have been reviewed in the literature relating to investigating the effect of TCSC on power system stability. Xu et al. [29] proposed TCSC controllers based on output feedback. In [30-31] identified the most effective signal in damping inter-area oscillations for a wide range of operating conditions using transfer function residues. In 1997, a time optimal control strategy was developed by Chang and Chow [32-33] for the TCSC control for damping inter-area modes in interconnected power systems. Therefore, H_∞ controllers have been proposed [34]. In [35-36] designed an output feedback VSC utilizing real and reactive power signals, which are local signals. The coordination of the proposed TCSC controller with a PSS was investigated [37-38]. Artificial neural networks are another form of the proposed self-tuning TCSC controllers in the literature [39-40]. Recently, heuristic optimization techniques have been implemented to search for the optimum TCSC based stabilizer parameters for the purpose of enhancing system stability. A GA and PSO based approach was developed to solve the optimization problem [41-44], and SA [45] to tune a conventional two-stage lead-lag controller for a TCSC. Table 1 show the complete list of TCSC installed worldwide as of December 2004 [46]. A robust nonlinear co-ordinated generator excitation and TCSC controller was proposed to enhance the transient stability of power systems [47-48]. Li [49] was proposed an impedance control strategy based on firing-angle modification feedback, which compared with that, based on impedance error modification feedback, avoids the firing-angle table search for each modification and speeds up the response of low-level control. Since many research did on this area [50-51]. Panda [52] investigated a systematic procedure for modeling, simulation and optimal tuning the parameters of a TCSC controller, for the power system stability enhancement.

Table 1 Complete list of TCSC installation

S.N	Year	Country	Voltage(kV)
1	1992	USA	230
2	1993	USA	500
3	1998	Sweden	400
4	1999	Brazil	500
5	2002	China	500
6	2004	India	400
7	2004	China	220

3.3 Static VAR Cmpensator (SVC)

SVC is an electrical device for providing fast-acting reactive power compensation on high voltage electricity transmission networks. SVCs are part of the FACTS device family, regulating voltage and stabilizing the system the system. 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 [53-71]. The low frequency oscillation damping enhancement via SVC has been analyzed [53-55]. Self-tuning and model reference adaptive stabilizers for SVC control have been proposed and designed [56]. Robust SVC controllers based on H∞, structured singular value μ, and quantitative feedback theory QFT has been presented to enhance system damping [57-58]. Genetic algorithms and fuzzy logic based approaches have been proposed for SVC control [59-63]. Optimal location of SVC was investigated in many researches [64-67]. Messina and Barocio [68] studied the nonlinear modal interaction in stressed power systems with multiple SVC voltage support. A robust nonlinear coordinated generator excitation and SVC controller was proposed to enhance the transient stability of power systems [69-70]. In [71], a sensitivity model for var dispatch was proposed to restore the var reserve of SVC while keeping desirable voltage profile and the control capability of SVCs was defined by the available control margin, the slopes, the reference voltage, the static voltage characteristic of the system.

4. Second Generation FACTS Devices

4.1 Static Compensator (STATCOM)

A STATCOM is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. Application of STATCOM for stability improvement has been discussed in the literature [72-90]. The effectiveness of the STATCOM to control the power system voltage was presented in [73]. In [74] was presented a singular value decomposition based approach to assess and measure the controllability of the poorly damped electromechanical modes by STATCOM different control channels. Haque [75] demonstrated by the use of energy function the capability of the STATCOM to provide additional damping to the low frequency oscillations. The STATCOM damping characteristics have been analyzed and addressed [76-84] where different approaches to STATCOM-based damping controller design have been adopted such as loop-shaping [78], pole placement [80], multivariable feedback linearization [81, 82], H_∞ control [83], and intelligent control [84]. Song [85] proposed A control scheme for star-connected cascade STATCOMs operating under unbalanced conditions. Shah [86] described an alternative STATCOM, by connecting a number of gate turn off thyristor converters in series on the ac side of the system. A novel interface neuro controller was proposed for the coordinated reactive power control between a large wind farm equipped with doubly fed induction generators and a STATCOM [87]. In [88] the control strategy for the STATCOM used in utility distribution systems were investigated and a novel fuzzy-PI-based direct-output-voltage control strategy was presented. Liu [89] presented a new feedback control strategy for balancing individual dc capacitor voltages in a three-phase cascade multilevel inverter-based static synchronous compensator. Xiang and Han [90] proposed a dynamic model for wind turbine-generator unit, including the wind-turbine and asynchronous induction generator.

4.2 Static Synchronous Series Compensator (SSSC)

The SSSC is a Series FACT Controller, becomes more attractive due to its superior abilities over the impedance-based series compensation. SSSC is a new series compensation equipment of FACTS. According to different operating conditions, its operation mode, control parameters and control strategy vary, and so the relay protection will be influenced inevitably The SSSC has been applied to different power system studies to improve the system performance [91-97]. There has been some work done to utilize the characteristics of the SSSC to enhance power system stability [98,99]. Wang [98] investigated the damping control function of an SSSC installed in power systems. In [99] was investigated the capability of the SSSC to control the line flow and to improve the power system stability. SSSC have been applied to different areas in power system studies including optimal power flow [100], damping oscillation [101-102] and optimal location for stability power system [103-104]. Vinkovic [105] presented a new approach to modelling a SSSC for power-flow calculations by applying the Newton-Raphson method. Panda presented an evolutionary multi-objective optimization approach to design a SSSC-based controller [106]. Hooshmand [107] used a SSSC along with a fixed capacitor in order to avoid torsional mode instability in a series compensated transmission system. In [108], a novel control strategy for subsynchronous resonance (SSR) mitigation using a SSSC was presented. Pradhanr [109] presented an analytical formulation of the frequency-domain characteristics of the SSSC.

4.3 Unified power Flow Controller (UPFC)

The UPFC is one of the most versatile topologies of the FACTS family. Researchers have developed different UPFC schemes in the literature [110-135]. Makombe and Jenkins [110] experimentally proved that a UPFC can control the three control parameters. High frequency power fluctuations, more than 100 Hz, induced by a UPFC have been investigated in [111]. Wang developed two UPFC models [112-113] which have been linearized and incorporated into the Phillips-Heffron model. A current injected UPFC model for improving power system dynamic performance was developed by Meng and So [115].

Schoder et al. [116] developed a UPFC model that can be suited for PST in MATLAB. Mishra et al. [117] and Schoder et al. [118] developed a Takagi-Sugeno (TS) type FL controller for a UPFC to damp both local and inter-area modes of oscillation for a multi-machine system. Dash et al. [119] suggested the use of a RBF NN for a UPFC to enhance system damping performance. Robust control schemes, such as H_∞ [120, 121] and singular value analysis [122] have been explored. A multi-input-multi-output (MIMO) PI controller has been proposed in [123-124]. An integrated linear and nonlinear control of a UPFC for stability enhancement of a multi-machine system was developed [125]. Sawhney [126] presented the application of one type of FACTS device, the UPFC to improve the transfer capability of a power system. An approach to solve first-swing stability problem using UPFC was proposed by Gholipour [127]. Fujita et al [128] presented dynamic control and performance of a UPFC intended for installation on a transmission system consisting of two sets of three-phase transmission lines in parallel. Al-Awami [129] investigated the use of the supplementary controllers of a UPFC to damp low frequency oscillations in a weakly connected system. In [130] was analyzed real, reactive power, and voltage balance of the UPFC system. Shaheen et al [131] proposed a Novel Nonlinear MIMO Predictive Control System using Optimal Control Approach to control UPFC. Singh et al [132] proposed new sensitivity factors to determine the optimal location of UPFC in the power systems. Shayeghi et al [133] presented a novel method for the design of output feedback controller for UPFC. Kang [134] presented a study on a small scale single-phase UPFC preliminary research on power quality compensating schemes of electrical railway. Ilango et al [135] investigated the application of multivariable control technique to MIMO non-linear problem of a power transmission system with UPFC.

4.4 Interline Power Flow Controller (IPFC)

The latest generation of FACTS devices, namely the IPFC, is the combination of multiple series compensators, which are very effective in controlling power flows in transmission lines. IPFC and the generalized unified power flow controller are two innovative configurations of the convertible static compensator of FACTS. Gyugyi et al [136] presented an IPFC which is a new concept for the compensation and effective power flow management of multi-line transmission systems. In [137] was presented a genetically optimized neuro-fuzzy IPFC for damping modal oscillations of power system. In [138] was reported on the results of studies performed to ensure satisfactory dynamic performance of the New York electric system with the UPFC and IPFC configurations of the Marcy Convertible Static Compensator. Wei et al [139] used injected voltage sources to directly model an IPFC and impose the rating limits in a Newton-Raphson load flow algorithm. Vasquez et al [140] investigated the operational analysis and the limitations of a GIPFC while interacting with the network. In [141-142] was investigates the damping control function of an IPFC installed in a power system. Zhang [143] presented, direct modeling of the practical series or/and shunt operating inequality constraints of the IPFC and the GUPFC in power flow calculations. Zhang and Chen [144] described a novel power injection model of IPFC for power flow analysis. Benysek [145] investigated the use of IPFC, which are dc/ac converters linked by common DC terminals, in a DG-power system from an economy perspective. Padiyar and Prabhu [146] proposed the modelling of IPFC with 12-pulse, three-level converters and the SSR. In [147] was presented the evaluation of the impact of the IPFC on available transfer capability enhancement. Azbe and Mihalic [148] proposed the basis for the implementation of such a strategy, In order to be able to successfully apply IPFCs for power-system transient-stability improvement. Moghadasi et al [149] investigated the impact of an IPFC on composite system delivery point and overall system reliability indices were examined. Parimi et al [150] investigated the use of the IPFC based controller in damping of low frequency oscillations. The Lyapunov energy-function approach was frequently used as a convenient way to control or analyze the electric-power system [151]. Bhowmick et al [152] proposed an advanced IPFC model to address this issue, wherein an existing power system installed with IPFC is transformed into an augmented equivalent network without any IPFC. Vinkovic and Mihalic [153] presented a new approach to modelling an IPFC for power flow calculations by applying the Newton-Raphson.

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. In addition, 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

Mostly, the location of FACTS devices depends on the objective of the installation. The optimal location can be governed by increasing system loadability [154-156], minimizing the total generation cost], and enhancing voltage stability [157]. Wang et al. [158] presented two indices for selecting the optimal location of PSSs or FACTS-based stabilizers. This work has been further developed in [159] where a new method independent of the eigensolution to identify the optimal locations and feedback signals of FACTS-based stabilizers was proposed. Yang et al. [160] applied the residue method to the linearized power system model to determine the location and the feedback signal of TCSC in a multi-machine power system. Kulkarni and Padiyar [161] proposed a location index based on circuit analogy for the series FACTS controllers. Rosso et al. [162] presented a detailed analysis of TCSC control performance for improving system stability with different input signals. Farsangi et al. [163] presented the minimum singular value, the right half plane zeros, the relative gain array to find the stabilizing signals of FACTS devices for damping inter-area oscillations. Ramirez and Coronado [164] 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. [165-166] 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. [167] presented two residue-based indices to identify an effective local signal that can be used by a TCSC as a supplementary controller to dampen inter-area oscillations for multiple power system operating conditions.

5.2 Coordination between Controllers

Uncoordinated FACTS-based stabilizers and PSSs always cause destabilizing interactions. To advance on the whole system performance, many researches were made on the coordination between PSSs and FACTS controllers. In [168-169] was presented the performance and interactions of PSS, SVC and TCSC. A technique for calculating the damping and synchronizing torque coefficients induced on generators by FACTS controllers based on modal analysis was proposed [170]. the interactions between PSSs and FACTS controllers in multi-machine systems was presented based on the analysis of both the perturbations in induced torque coefficients and the shifts in rotor modes resulting from increments in stabilizer gains [171]. A new unified Phillips-Heffron model for a power system equipped with a SVC, TCSC and TCPS was proposed [172-173]. A Nonlinear control method was introduced to design a coordinated excitation and TCPS controller [174], and a coordinated excitation and UPFC controller [175] to increase damping of oscillation. Lee et al. [176] presented an observer-based decentralized optimal control design of a PSS and a TCSC used to a multi-machine system. Also Li et al. [177-178] proposed a similar method to design a coordinated optimal controller to implement multiple TCSCs in a multi-machine system. H_∞ control scheme has been employed to tune decentralized SVC and TCSC controllers using a model-matching robustness formulation [179]. Moreover Sanchez-Gasca [180] presented a coordinated controller for a TCSC and a TCPS using projective control scheme. Pourbeik and Gibbard [181] presented a two-stage method for the simultaneous coordination of PSSs and FACTS-based lead-lag controllers. Fang and Ngan [182] changed the problem of simultaneously selecting the controller settings of a PSS and a MIMO controller of a UPFC into an optimization problem. Ramirez et al. [183] investigated a similar advance to design a PSS, TCSC and UPFC lead-lag controllers. Lie et al. [184] presented the same technique to find the optimal settings of coordinated PSS, SVC and TCSC lead-lag controllers. Panda and Padhy [185] proposed the application of GA for the design of a PSS and a FACTS-based controller. In [186] power system multi input-multi output identification methods that were useful for simultaneous coordinated design of PSS and TCSC controller were presented. Panda and Patel [187] proposed a procedure for modeling and simultaneous tuning of parameters of TCSC controller and PSS in a power system to damp power system oscillations. A fuzzy controller was used [188] to design both FPSS and FFDC in multi machine power system for increase of damping the power system oscillation. Fang et al. [189] proposed a nonlinear programming model for simultaneously coordinated parameters design of PSS and STATCOM stabiliser. A modified simplex-simulated annealing algorithm was developed for solving the programming model. A multi-objective evolutionary algorithm based approach to PSS and SVC tuning was introduced [190]. A coordinated design of robust PSS and SVC damping controller in a multi-machine power system was investigated [191]. A linearized system model and the parameter-constrained nonlinear optimization algorithm was proposed in [192].

6. FACTS Technology Implementation & Development

6.1 FACTS Installations and Utility Experience

In the starting to appear deregulated power systems, FACTS controllers will supply some advantages at existing or improved levels of reliability such as balancing the power flow in parallel networks over a wide range of operating conditions, mitigating inter-area power oscillations, alleviating unwanted loop flow and intensification the power-transfer capacity of existing transmission corridors [193]. In 1991, a ±80 Mvar STATCOM extended by Kansai Electric Power Co. and Mitsubishi Motors was fixed at Inuyama Switching Station to improve the stability of a 154 kV system [194]. A ±100 Mvar STATCOM was ordered for the Tennessee Valley Authority in 1995 [195-196]. The TVA STATCOM is the first of its kind, using GTO thyristor valves, to be ordered in USA. In 1997, American Electric Power has selected its Inez substation in eastern Kentucky for the location of the world's first UPFC installation [197-198]. 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, 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 [199]. A ±75 Mvar STATCOM developed by ALSTOM, the first cascade multilevel-inverter-based STATCOM in the world, entered commercial service at National Grid Company East Claydon, England in 2001 [200]. A +133/-41 Mvar STATCOM system has been installed at the Vermont Electric Power Company's Essex 115 kV substations since May 2001, to compensate for heavy increases in summertime electric usage [201]. A three-level ±100 Mvar STATCOM is installed by San Diego Gas & Electric at Talega substation, California in October 2002, and is to be extended to a Back-To-Back system [202]. ABB has installed six STATCOM systems since 1997; two installations in USA and one installation in Sweden, Germany, Finland, and France [203]. A ±250 Kvar prototype D-STATCOM was designed and installed for the first time [204]. More FACTS installations to improve the performance of different power system utilities can be found in [205]. A ±50 Mvar STATCOM based on chain circuit converter employing IGCTs has been developed successfully and has been put into operation [206]. The Puerto Rico Electric Power Authority suffered a major power plant failure in Palo Seco in late 2006.The network planners were facing a severe problem with potential voltage stability in the area, and decided that the most expedient solution to the problem while the power plant was being refurbished was an SVC rated at 0/+90 Mvar [207]. Georgia Transmission Corporation commissioned the Barrow County SVC with a continuous rating of 0 to +260 Mvar in June of 2008 [208].

6.2 FACTS Devices Technology Development

The technology behind thyristor-based FACTS controllers has been present for several decades and is therefore considered mature. A relatively new device called the Insulated Gate Bipolar Transistor has been developed with small gate consumption and small turn-on and turn-off times. 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) [209, 210]. The ratings of IGCT reach 5.5 kV/1.8 kA for reverse conducting IGCTs and 4.5 kV/4 kA for asymmetrical IGCTs [211]. Currently, typical ratings of IGCTs on the market are 5.5 kV/2.3 kA (ABB) and 6 kV/6 kA (Mitsubishi) [209]. Injection Enhanced Gate Transistor 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. The ratings of IEGT are in the order of 4.5 kV/1.5 kA [212]. 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. A modular ETO-based 1.5 MVA H-bridge converter is used to build a cascaded-multilevel converter for high power FACTS devices [213, 215]. A novel approach to distributed FACTS controllers based on active variable inductance has been recently proposed to realize cost-effective power flow control [216]. 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 [217].

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. Fig. 6 show summarizes the impact of FACTS on load flow, stability and voltage quality when using different devices. Evaluation is based on large number of studies and experiences from projects. 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. Generally in power flow studies, the thyristor-controlled FACTS devices, such as SVC and TCSC are usually modelled as controllable impedance [218-220]. However, VSC-based FACTS devices, including IPFC and SSSC, shunt devices like STATCOM, and combined devices like UPFC, are more complex and usually modelled as controllable sources [221-222]. A new hybrid model for OPF incorporating FACTS devices was investigated to overcome the classical optimal power flow algorithm where load demands, generation outputs, and cost of generation are treated as fuzzy variables. An improved GA was presented to solve OPF problems in power system with FACTS where TCPS and TCSC are used to control power flow [223-224]. 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. A linear programming -based OPF algorithm was proposed for corrective FACTS control to relieve overloads and voltage violations caused by system contingencies [225]. The optimization objective was chosen to minimize the average load ability 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. In [226] 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.

Table 2 Cost of conventional and FACTS controllers

FACTS Controllers	Cost(US $)
Shunt Capacitor	8/kVar
Series capacitor	20/kVar
SVC	40/kVar controlled portions
TCSC	40/kVar controlled portions
STATCOM	50/kVar
UPFC Series Portions	50/kVar through power
UPFC Shunt Portions	50/kVar controlled

8. Costs

As compared to conventional devices, FACTS controllers are very expensive. The approximate cost per KVar output of various conventional devices and FACTS controllers are shown in Table 2. However, the cost per KVar decreases for higher capacity of FACTS controllers. The total cost also depends on the size of fixed and controlled portion of the FACTS controllers. The FACTS equipment cost represent only half of the total FACTS project cost. Other costs like civil works, installation, commissioning, insurance, engineering and project management constitute the other half of the FACTS project cost.

9. Conclusion

This paper presented an extensive analysis on the research and improvements in the power system stability development using FACTS devices. The necessary features of FACTS controllers and their potential to increase system stability investigated. Moreover, some of the utility experience, real-world installations, and semiconductor technology development have been outlined.The location and feedback signals used for design of FACTS-based damping controllers were discussed. About two hundred 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.

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