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FACTS: CHARACTERISTICS, APPLICATIONS AND ECONOMIC VALUE. A LITERATURE REVIEW

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ABSTRACT
In today's competitive power markets, under the pressure of fast increasing demands and interregional trades, how to make the better use of the present transmission system, while still satisfying required reliability standards is gaining more and more attention. In this context, FACTS devices offer great opportunities in modern power system because of their great flexibility, controllability and overall performance, allowing better and safer operation of the grid. This paper gives a brief introduction of various kinds of FACTS devices and their controllers, some key research areas and various applications. We also present a survey on both the technical benefits that FACTS devices can bring to the system and the valuation of their economic benefits. We conclude that there is a large literature body on technical issues associated with FACTS, but limited work on valuing those benefits, offering great research opportunities.

KEY WORDS
FACTS devices, optimal powef flow, economic evaluation.

1. Introduction

The concept of FACTS (Flexible AC Transmission Systems) and FACTS controllers was first defined by Hingorani, 1988 in [1]. They usually refer to the application of high-power semiconductor devices to power systems, providing different services whose origin is on the high speed control of different parameters and electrical variables, such as voltage, impedance, phase angle, current, reactive and active power, etc.

FACTS technology can significantly improve the steady-state as well as the transient performance of power systems, including improvements in reliability [2][3][4], power flow and voltage control [5][6][7][8], oscillation damping [9][10][11], and transient stability improvement [12]. It also has impacts on important issues in deregulated electricity markets, such as available transfer capability (ATC) / total transfer capability (TTC) [13][14], congestion management [15][14][16], transmission pricing [17][18][16][19], and transmission rights auctions [20].

Optimal location of FACTS devices can help obtain the best control effects for the power system [21], while their optimal configuration helps making the best investment [22] by choosing the most suited technology, size and utilization. Since FACTS devices require huge investment costs that are often comparable to those of new transmission lines (Mutale and Strbac [23]), it is essential to clearly identify the economic benefits of these devices [23][24][25][26], this being one of the motivations of this paper.

Over the past 20 years, many techniques have been used to improve power system performance by applying FACTS devices, including novel formulations of optimal power flow (OPF) [27][4][15][14][19][18][23][25][22][13], sensitivity methods [28], probability methods [2][3][4], etc. Since FACTS control is a continuous variable problem, OPF is still the first choice for addressing FACTS control [27]. Nonetheless, many other techniques, such as genetic algorithms [29][30] , simulated annealing and tabu search methods [30], augmented lagrange multiplier [31], mixed integer nonlinear programming [17], and sequential quadratic programming [26] have been employed to solve OPF problems with embedded FACTS devices.

In this paper, the general concepts of various FACTS devices, their control attributes and their applications are briefly reviewed. Applications and methods on technical and economic benefits of FACTS are explained in detail. Finally, some directions for future research in this field are given.

2. FACTS Devices and Their Controllers

In this section we briefly describe the main families of FACTS devices, the semiconductor families they rely on, their operating principles and their main features.

2.1 FACTS devices: general concepts and definitions

FACTS technology is a collection of controllers that can be applied to control a set of inter-related electrical variables and parameters ([32] pg. 3), providing great flexibility to the system operator, enhancing the opportunities to perform various functions as we pointed out above. This provides many benefits that lie in various different dimensions, some of which are pointed out next.

FACTS devices are classified in two families, according to the family of semiconductor gates they use: Thyristor-based FACTS and FACTS based on fully controlled semiconductor devices. The former are based on older but less expensive line-commutated thyristor technology [33], while the later are based on newer fully-controllable switching technology that allows for high frequency switching, such as self-commutated thyristors/transistors GTOs, GCTs, IGCTs, and IGBTs [34]. This makes generating reactive power possible without large reactive energy storage elements, by circulating current through the phases of the AC system ([35] pg. 28). For economical and performance reasons, these converters are usually based on Voltage Source Converters (VSC) using a capacitor in the dc-side, rather than Current Source Converter ([35] pg. 29).

Thyristor-Controlled Reactor (TCR), Static Var Compensator (SVC), Thyristor-Controlled Series Compensator (TCSC), Thyristor Controlled Phase-Shifting Transformer (TCPST), Dynamic Flow Controller (DFC) and Thyristor-Controlled Voltage Regulator (TCVR) are thyristor-based, while STATic synchronous COMpensator (STATCOM),Static Synchronous Series Compensator (SSSC), Unified/Interline Power Flow Controller (UPFC/IPFC) all use VSCs.

TCR is a shunt-connected reactor whose effective reactance is varied in a continuous manner by partial conduction control of the thyristor valve [34].

SVC consists of a TCR in parallel with a capacitor bank. It behaves like a shunt-connected variable reactance to regulate the voltage at the point of connection by generating or absorbing reactive power [35].

TCSC consists of a series capacitor paralleled by a thyristor-controlled reactor to provide smooth variable series compensation and power flow control. It resembles the conventional series capacitor [34][35] and is very similar to a SVC, but it is usually series connected with a transmission line, instead of shunt connected with a local bus [35].

TCPST acts by adding a quadrature component to the prevailing bus voltage to increase or decrease its angle [36][30], controlling power flow and mitigating loop flows.

TCVR operates by inserting an in-phase voltage to the main bus voltage to change its magnitude [30], also providing reactive power flow control.

STATCOM can be equivalently represented by a controllable fundamental frequency positive sequence voltage source. It is usually used to control transmission voltage by reactive power shunt compensation [35].

SSSC is similar to the STATCOM but it is connected in series with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at one of the terminals of the series-connected transformer [35][34].

UPFC consists of two VSCs connected by a common DC link ([34] pg. 36). This is a series unit (SSSC) connected with a shunt one (STATCOM) ([37] pg. 23). The series inverter is coupled to a transmission line via a series transformer. The shunt inverter is coupled to a local bus via a shunt-connected transformer. The shunt inverter can generate or absorb controllable reactive power, and it can provide active power exchange to the series inverter to satisfy operating control requirements [34][35].

Most VSC-based FACTS applications have only two converters [38]. However, theoretically, as long as the power balance requirements are satisfied and controls can be successfully implemented, more converters can be interconnected to form a single FACTS controller [38] to control power flows of multi-lines or a subnetwork [34]. Examples include the Generalized Unified Power Flow Controller (GUPFC) and IPFC.

GUPFC combines three or more converters to fulfill multi-line voltage and power flow control. The simplest GUPFC consists of three converters, one connected in shunt and the other two in series with two transmission lines exiting a substation [38][34]. This GUPFC can control a bus voltage and independent active and reactive power flow of two lines ([34] pg. 23). Its mathematical model can be found in [38][34]. The IPFC consists of two series-connected VSCs whose DC capacitors are coupled. This allows active power to circulated between the VSCs. It can be used to control the power flows of two lines starting in one substation ([34] pg. 22).

2.2 Faster direct AC-AC conversion

There is also an important area of research on Vector Switching Converters (VeSCs). They perform direct ac-ac conversion without frequency change, relying in much faster switching, typically pulse width modulation, than previous technologies (Thyristor-based SVCs and TCSCs).

For a closer look into VeSCs, their operating principles and models for power flow control visit [39]. We don't further develop this area, because we are interested in "broadly" used FACTS devices for power systems. Nonetheless, as new faster-high power semiconductors become available and prices fall, we expect these technologies to have their place into the power system.

2.3 FACTS devices' control attributes

Since electrical variables and parameters, such as currents, voltages, impedances, active and reactive power, etc. are closely interrelated, each FACTS device can provide multiple benefits,some of them are listed next ([40] pg.26): TCR, SVC, STATCOM, TCSC, SSSC, UPFC, IPC, TCPST can each perform voltage control and oscillation damping [35].

TCVR, TCSC, UPFC, IPC, TCPST can control power flow for reducing overload [35][40], parallel line load sharing [35], post fault power flow sharing [35]. Among them, UPFC can perform both active and reactive power flow control [40], while TCPST can only control active power flow [40] and TCVR only reactive power flow [40]. Moreover, UPFC, IPC, SSSC and TCPST can adjust phase angle to prevent power flow direction reversal [35]. IPFC and GUPFC have extended capabilities to control power flows of multi-lines or a sub-network, beyond that achievable by the UPFC, SSSC or STATCOM ([34] pg.70).

2.4 FACTS devices' steady-state model

FACTS devices modeled at steady-state are presented in [34][35][20][17][41]. Power injection model is a choice for TCSC [11], SVC [17][18][13][29], TCPST [11][29], and UPFC, IPFC, SSSC, STATCOM, GUPFC [11][8][5]. TCSC can also be modeled as controllable impedance [35][17][14][18][42][30][29][28][20][10], so does SVC [35][30]. SVC can also be modeled as a ficticious PV bus [4][14] when installed in middle of the transmission line, but resulting in a non-desirable modification of the Jacobian structure [20][17][41]. TCPST also is modeled as ideal phase shifter [36][30][28][20], Thyristor controlled phase angle regulator (TCPAR) is represented by a phase shifting controller with complex phase angle α [4][42], or a series inserted voltage source and a tapped current [17]. VSC based FACTS devices, because of their complexity, are usually modeled as controllable voltage/current sources [35][43], but it destroys the symmetric characteristics of admittance matrix [20][17][41].

The equations for static modeling of SVC, TCSC and TCPAR in optimal power flow formulation are given by Chanana [17]. Canizares and Faur [7] give more detailed steady-state models with controls of SVCs and TCSCs to study their effect on voltage collapse phenomena.

2.5 FACTS devices' practical applications

The potential benefits of FACTS devices are widely recognized. There are many hundreds of applications of SVCs for voltage control through reactive compensation starting in the mid 1970s [44]. There are also a couple of dozen of TCSCs and STATCOMs. "A couple of years ago, TCSCs reached commercial application" [45], major examples of which include TCSCs at Bonneville Power Administration's Slatt substation [33], TCSC at Western Area Power Administration's Kayenta site, USA [45], and TCSC in Stoede, Sweden [45]. On transmission level, the first SVC was used in 1979 ([34], Pg. 12). The first TCSC was commissioned in 1996 ([34], Pg. 18). There are also a few pilot projects for STATCOMs, such as projects of Sullivan substation in North-Eastern Tennessee [33], VELCO Essex [33], SDGandE Talega [33], Glenbrook 115KV Substation in Stamford, Connecticut [33]. The first SVC with VSC called STATCOM went into operation in 1999 ([34], pg.13). FACTS devices based on multiple VSCs, providing multi-parameter control of single line or even multi transmission lines such as UPFC, GUPFC and IPFC, are the most modern solutions. Huge investments and complex control strategies limit their application. There are only very few pilot projects, such as World's first UPFC at Inez, USA [33] and a Convertible Static Compensator (CSC) introduced by the New York Power Authority (NYPA) [33]. The CSC has two converters and can function as a STATCOM, SSSC, UPFC, or IPFC through appropriate arrangement of disconnect switches and circuit switchers.

3. Optimal Power Flow Formulation

The optimal power flow (OPF) is an important method used in many different areas in power systems. For our purpose, we could refer to the OPF as a modified power flow problem, able to adjust some power system settings (such as generators' power outputs and voltages, transformer taps, etc.) in a predefined optimal fashion. Many successful OPF techniques already developed can easily be upgraded to accommodate FACTS constraints into the problem [27].

As an optimization problem, OPF consists of an objective function to be minimized or maximized with a set of equality and inequality constraints. The objective function could consider maximizing power transferred at objective buses or interface [20][13], minimize generation costs [19][18][16][29][17][23][24][25][26], minimize transmission lines' loadability [5][30], transmission losses [31], voltage fluctuation [30], the installation cost of FACTS devices [31][29][17], and curtailed transactions [14], maximize/minimize FACTS devices total transferred power [22], or a multi-objective function expressed as a weighted combination of objectives listed above [30][31][29][17].

The equality constraints are usually the power balance at each bus. Some papers only use real power constraints [23][25][24][20], but most papers also include reactive constraints [26][29][17][22][31][16][18][14][15][5][4][13]. Inequality constraints include power generation limits, power consumption limits, power factor constraint, transmission limits, and FACTS' operation constraints [20][29][4][14][18][31][22][17][16][14][26][13]. Besides these, voltage limits [4][14][18][31][22][17][13], phase angle limits [16], and sometimes market constraints for specific application [14][26] are also considered as inequality constraints.

DC power flow [20][23][24][25], AC power flow [15][14][18][16][26][29][17][22][31][13], or linearized AC power flow [5] can be used when incorporating FACTS devices into OPF, depending on the FACTS devices being considered and the application. A literature review on OPF incorporating FACTS devices is given in [27].

4. Main Application

The impact of FACTS devices on system security [2][3][4][5][9][7][6][10][11], issues regarding to TTC/ATC [13][14], congestion management [15][14][16], transmission pricing [17][18][16][19], transmission rights auctions [20] in a deregulated environment and how to choose their optimal location to achieve the best control effects [21] has been studied to a limited extent.

4.1 Security improvement

Billinton [2][3] uses a probability method to evaluate power system reliability when incorporating FACTS devices. He considers the power system as a meshed complex network, and a multi-source multi-sink maximum flow instead of

power flow. Huang [4], using the same probability method, however, chooses the power flow equations considering FACTS effect as equality constraints.
Shao [5] provides a sensitivity method to incorporate nonlinear UPFC operational constraints in a LP-based OPF to relieve overloads and voltage violations caused by system contingencies. By using LP-based OPF, the speed requirement of corrective control can be satisfied.
Mhaskar [9] investigates the properties of zero locations and duality between modal controllability and modal observability when certain local signals are used for SSSC-based damping controllers. Fujita [6] presents dynamic active power flow control and behavior of a UPFC under a fault condition in a transmission system consisting of two parallel lines. Simulation shows good transient performance without any overshoot or oscillation. Larsen [10] gives key insights to aid the task of designing FACTS controllers to damp interarea power oscillations.
Noroozian [11] uses UPFC, TCPST and TCSC to damp electromechanical power oscillations. An energy function based control strategy is derived. The achieved control laws are shown to be effective both for damping of large signal and small signal disturbances and are robust with respect to loading condition, fault location and network structure.

4.2 FACTS in deregulated power systems

FACTS technology plays an important potential role in power markets, as they greatly impact the way the system is operated, especially with respect to thermal, voltage and dynamic constraints [23] and these operational changes translates directly into changes in the electricity market. FACTS devices' impacts related to TTC / ATC [13][14], congestion management [15][14][16], transmission pricing [17][19][18][16] and transmission rights auctions [20] have been partially studied.
Xiao [13] proposes an OPF based ATC enhancement model to achieve the maximum power transfer of the specified interface with SVC, TCPST, UPFC. Phichaisawat [15] and Huang [14] investigate impacts of FACTS devices on congestion management. Both active and reactive congestion are considered in [15]. Market separation constraints are used in [14]. Methods in both papers are applicable to both pool markets and bilateral markets.
Oliveira et al. [19] have shown the ability of FACTS devices to change the production cost and their impact on transmission charges. They also show that the effect of FACTS devices on transmission charge varies according to the pricing methodology adopted. They also consider production cost minimization as the objective function.
Srivastava and Verma [18] describe an approach of transmission pricing calculation taking social welfare maximization as the objective and study the impact of TCSC and SVC on real and reactive spot prices and wheeling rate.
Verma and Gupta [16] present a methodology to locate UPFC for congestion management in the deregulated power sector and present a nonlinear formulation with UPFC to show its impact on real and reactive spot pricing.
Wang [20] models two types of series FACTS devices into a DC power flow to model a Financial Transmission Rights (FTR) auction. TCSC and TCPS are modeled as additional power injection at buses in the linear optimization problem of FTR auction.

5. Economic Value of FACTS

While a significant amount of work has been and continues to be devoted to the description and analysis of the technical performance of FACTS, very few papers have been published on the economics of these devices. Various papers [23][24][25][26] try to maximize the social welfare, but the investment cost of FACTS are not considered, as it is in [29][17]. While others [22][31] focus on the FACTS device itself to make an optimal investment.
Mutale and Strbac [23] compute the maximum savings in operating costs that could be secured from installing FACTS. Only the thermal capacities of the circuits are considered to assess FACTS devices against network reinforcement. In his method, a constant marginal cost for generators is assumed. Only the gross benefit of FACTS is considered.
Schaffner and Andersson [25] compare a DC power flow based OPF algorithm with Copper Plate Model on valuating TCSC with maximizing social welfare. In [24], they choose the Copper Plate Model, combined with financial instruments to determine the value of FACTS devices. In both papers, only the supply bids are included when maximizing social welfare.
Lehmkoster [26] uses sequential quadratic programming to find the optimal use of the existing power systems with embedded UPFC. The objective is to minimize the cost, including generation cost, cost of unserved load and the cost between an actual and a scheduled transaction. Cai [29], Chanana [17] and Fang [31] consider economic impacts of FACTS when deciding their optimal location. While [29] includes only the supply bids for real power, [17] also includes the bids for reactive power and [31] integrates in the objective function the investment on UPFCs and real power loss of the network. Fardanesh [22] provides a method to determine the optimal combination of shunt and series capacities of FACTS devices, maximizing FACTS devices' total transferred power.

6. Conclusion

This paper surveys FACTS devices' role in various aspects of power systems, their technical benefits and economic value. FACTS devices have already been presented as an alternative to reduce the flows in heavily loaded lines, resulting in an increased loadability, lower system losses, improved stability of the network, reduced cost of production, and fulfill more closely contractual requirement by power flows control [16]. There are already plenty of work done focusing on these technical benefits of FACTS devices.

Optimal power flow is the preferred tool for solving problems in power system with FACTS devices. By choosing proper objective function and necessary equality and inequality constraints, it is possible to incorporate FACTS and their operational limits into OPF. The question of which objective function and constraints should be included still remains. Its answer depends on the specific goals of the study. We find very limited literature on valuing the economical benefits of FACTS devices. The main problem is that FACTS devices affect everything, from operation, transmission utilization, security and reliability scenario to the electricity market and its components.

This also makes it very difficult to come up with a single model that can assess all or most of these benefits, as the appropriate model to asses each of them is probably different. For instance, while addressing network utilization or short-term social welfare maximization, it may suffice to use a steady state OPF model, the inclusion of voltage control, transient stability and oscillation issues requires the inclusion of ad-hoc (and to certain extent arbitrary) modifications into the OPF formulation.

The transition to a more sophisticated power system where FACTS devices play a more important role in the system operation, requires the development of proper tools to assess both technical and economic benefits and their valuation. We believe that most models presented so far are not able to properly value FACTS benefits, leading to undervaluation of them and correspondingly underprovision of FACTS in the system. This is certainly an area that requires more research.

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