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FLEXIBLE AC TRANSMISSION SYSTEM

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ABSTRACT

The AC transmission system has various limits classified as static limits and dynamic limits [1-3]. These inherent power system limits restrict the power transaction, which lead to the under utilization of the existing transmission resources. Traditionally, fixed or mechanically switched shunt and series capacitors, reactors and synchronous generators were being used to solve much of the problem. However, there are restrictions as to the use of these conventional devices. Desired performance was not being able to achieve effectively. Wear and tear in the mechanical components and slow response were the heart of the problems. There was greater need for the alternative technology made of solid state devices with fast response characteristics. The need was further fuelled by worldwide restructuring of electric utilities, increasing Environmental and efficiency regulations and difficulty in getting permit and right of way for the construction of overhead transmission lines [4]. This, together with the invention of Thyristor switch (semiconductor device), opened the door for the development of power electronics devices known as Flexible AC Transmission Systems (FACTS) controllers. The path from historical Thyristor based FACTS controllers to modern state-of-the-art voltage source converters based FACTS controllers, was made possible due to rapid advances in high power semiconductors devices [1-3]. FACTS controllers have been in use in utilities around the world since 1970s, when the first utility demonstration of first family of FACTS named as Static Var Compensator (SVC) was accomplished. Since then the large effort was put in research and development of FACTS controllers.

KEYWORDS: AC Transmission, High-Power Electronics, Flexible AC Tranmission, SVC

INTRODUCTION

History of Development and Status Static Var Compensator

Static Var Compensator is the most primitive and first generation of FACTS controllers. Electric Power Research Institute (EPRI) brings this technology to the market three decade ago. This compensator consists of a fast thyristor switch controlling a reactor and/or shunt capacitor bank, to provide dynamic shunt compensation. More than 800 SVCs are being installed worldwide, both for utility and industrial (especially in electric arc furnace and rolling mills) application. Even the utilities in developing countries took the benefit of SVCs since its invention.

ABB remains the pioneer in deployment of SVC and has supplied 55% of the total installation of which 13% were being installed in Asian countries. The world’s first demonstration of SVC for utility application was installed in 1974, which was commercialized by General Electric (GE) [1].

As a consequence of deregulation in UK in 1990, voltage control became difficult. To accommodate the risk associated with the uncertain future and changing power system condition, UK installed relocatable SVC (RSV). At present 12 RSVC (60 MVAr each) are operational in the NGC (National Grid Company) system [5].

THYRISTOR CONTROLLED SERIES CAPACITOR

Thyristor Controlled Series Capacitor (TCSC) is a later member of the first generation of FACTS devices, that uses silicon controlled rectifiers to manage a capacitor bank connected in series with a line. TCSC allows utility to transfer more power further on a particular line. The worlds first three phase TCSC was developed by ABB and installed at Kayenta substation, Arizona in 1992, that raises the capacity of a transmission line by almost 30%. By the end of year 2004, seven TCSCs have been installed worldwide. In Asia, three TCSC came into operation; two in China and one in India, bringing Asia into the forefront of the advanced FACTS technology. Table 1 shows the complete list of TCSC installed worldwide as of December 2004.

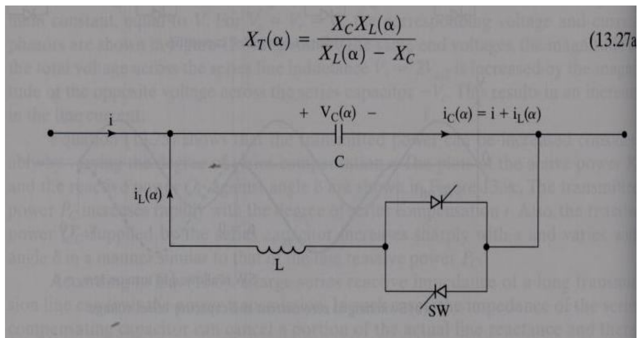

FIGURE 13.11
Thyristor-controlled series capacitor (TCSC).

Static Synchronous Compensator (STATCOM) is the second generation of FACTS controllers that has a very promising future application. STATCOM has several advantages of being small/compact, high response speed and no harmonic pollution. The world's first commercial STATCOM (± 80 MVA, 154 kV) was developed by Mitsubishi Electric Power Products, Inc and was installed at Inuyama substation in Japan in 1991. There are around 20 STATCOM operating successfully around the world. Table 2 lists some major utility scale STATCOMs which are in operation.

STATIC SERIES SYNCHRONOUS COMPENSATOR

Static Series Synchronous Compensator (SSSC) is a complementary second-generation FACTS controller, which is simply a series version of STATCOM. SSSC are not yet in commercial operation as an independent controller.

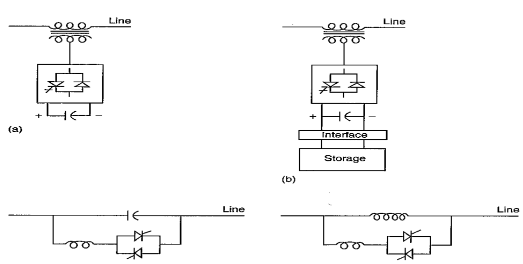

Figure 1.6 (a) Static Synchronous Series Compensator (SSSC); (b) SSSC with storage; (c) Thyristor-Controlled Series Capacitor (TCSC) and Thyristor-Switched Series Capacitor (TSSC); (d) Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Switched Series Reactor (TSSR).

UNIFIED POWER FLOW CONTROLLER

Combining the STATCOM and the SSSC into a single device with a common control system represents the third generation of FACTS known as Unified Power Flow Controller (UPFC). It has the unique ability to control real and active power flow independently. The first utility demonstration of a UPFC is being constructed at the Inez substation of American Electric P

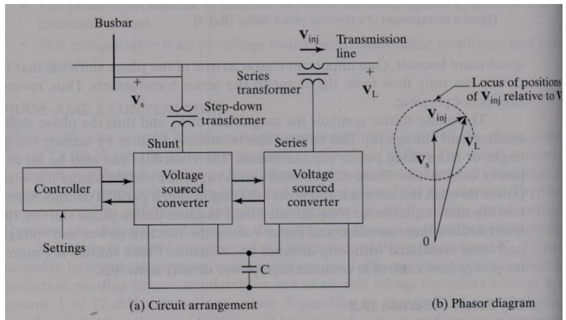

FIGURE 13.19
Unified power flow controller [Ref. 4].

CONVERTIBLE STATIC COMPENSATOR

The most recent development in the field of FACTS controllers is the "Convertible Static Compensators (CSC)". The CSC offers the full flexibility by allowing its converters to be connected in shunt (STATCOM), in series (SSSC), in shunt/series (UPFC) or in series/series Interline Power Flow Controller (IPFC) with two lines. The worlds first CSC is installed at New York Power Authority's Marcy 345 kV substation, which is capable of operating in eleven different control modes.

Table 1: Complete list of TCSC installation

S.N	Year Installed	Country	Voltage level (kV)	Purpose	Place
1	1992	USA	230	To increase power transfer capability	Kayenta substation, Arizona
2	1993	USA	500	Controlling line power flow and increased loading	C.J.Slatt substation in Northern Oregon
3	1998	Sweden	400	Sub Synchronous Resonance mitigation	Stöde
4	1999	Brazil	500	To damp inter-area low freq (0.2 Hz) oscillation	One at Imperatriz and another one at Sarra de Mesa
5	2002	China	500	Stability improvement, low-frequency oscillation mitigation	Pinguo substation, State power south company, Guangzhou
6	2004	India	400	Compensation, Damping interregional power oscillation	Raipur substation
7	2004	China	220	Increase Stability margin, suppress low frequency oscillation	North-West China Power System

Table 2: Partial list of utility scale STATCOM

S.N	Year Installed	Country	Capacity, MVAR	Voltage level (kV)	Purpose	Place
1	1991	Japan	± 80 MVA	154	Power system and voltage stabilization	Inumaya substation
2	1992	Japan	50 MVA	500	Reactive compensation	Shin Shinano Substation, Nagona
3	1995	USA	± 100 MVA	161	To regulate bus voltage	Sullivan substation in TVA power system
4	2001	UK	0 to +225	400	Dynamic reactive compensation	East Claydon 400 kV Substation
5	2001	USA	-41 to +133	115	dynamic reactive compensation during critical contingencies	VELCO Essex substation
6	2003	USA	± 100	138	dynamic var control during peak load conditions	SDG&E Talega substation

Table 3: Complete list of TCSC installations

S.N	Year Installed	Country	Capacity , MVA	Voltage level (kV)	Purpose	Place
1	1998	USA	± 320	138	Dynamic voltage support and added real power supply facility	AEP Inez substation
2	2003	South Korea	80	154	Dynamic voltage support and added real power supply facility	Gangjin substation

FACTS APPLICATION

FACTS controllers can be used for various applications to enhance power system performance. One of the greatest advantages of using FACTS controllers is that it can be used in all the three states of the power system, namely: (1) Steady state, (2) Transient and (3) Post transient steady state. However, the conventional devices find little application during system transient or contingency condition.

STEADY STATE APPLICATION

Various steady state applications of FACTS controllers includes voltage control (low and high), increase of thermal loading, post-contingency voltage control, loop flows control, reduction in short circuit level and power flow control. SVC and STATCOM can be used for voltage control while TCSC is more suited for loop flow control and for power flow control.

Congestion Management

Congestion management is a serious concern for Independent System Operator (ISO) in present deregulated electricity markets as it can arbitrarily increase the prices and hinders the free electricity trade.

FACTS devices like TCSC, TCPAR (Thyristor Controlled Phase Angle Regulator) and UPFC can help to reduce congestion, smoothen locational marginal prices (LMP) and to increase the social welfare by redirecting power from congested interface to under utilized lines [7-8].

ATC Improvement

In many deregulated market, the power transaction between buyer and seller is allowed based on calculation of ATC. Low ATC signifies that the network is unable to accommodate further transaction and hence does not promote free competition. FACTS controllers like TCSC, TCPAR and UPFC can help to improve ATC by allowing more power transactions [9-10].

Reactive Power and Voltage Control

The use of shunt FACTS controllers like SVC and STATCOM for reactive power and voltage control is well known [11-13].

Loading Margin Improvement

Several blackouts in many part of the world occurs mainly due to voltage collapse at the maximum loadability point. Series and shunt compensations are generally used to increase the maximum transfer capabilities of power networks. The recent advancement in FACTS controllers have allowed them to be used more efficiently for increasing the loading margin in the system [14-15].

Power Flow Balancing and Control

FACTS controllers, especially TCSC, SSSC and UPFC, enable the load flow on parallel circuits and different voltage levels to be optimized and controlled, with a minimum of power wheeling, the best possible utilization of the lines, and a minimizing of overall system losses at the same time.

DYNAMIC APPLICATION

Dynamic application of FACTS controllers includes transient stability improvement, oscillation damping (dynamic stability) and voltage stability enhancement. One of the most important capabilities expected of FACTS applications is to be able to reduce the impact of the primary disturbance.

The impact reduction for contingencies can be achieved through dynamic voltage support (STATCOM), dynamic flow control (TCSC) or both with the use of UPFC.

Transient Stability Enhancement

Transient instability is caused by large disturbances such as tripping of a major transmission line or a generator and the problem can be seen from the first swing of the angle. FACTS devices can resolve the problem by providing fast and rapid response during the first swing to control voltage and power flow in the system [16].

Oscillation Damping

Electromechanical oscillations have been observed in many power systems worldwide and may lead to partial power interruption if not controlled. Initially, power system stabilizer (PSS) is used for oscillation damping in power system. Now this function can be more effectively handled by proper placement and setting of SVC, STATCOM and TCSC [17-18].

Dynamic Voltage Control

Shunt FACTS controllers like SVC and STATCOM as well as UPFC can be utilized for dynamic control of voltage during system contingency and save the system from voltage collapse and blackout.

SSR Elimination

Subsynchronous resonance (SSR) is a phenomenon which can be associated with series compensation under certain adverse conditions. TCSC have dynamic characteristics that differ drastically from conventional series capacitors especially at frequencies outside the operating frequency range and hence is used in Stöde, Sweden for the elimination of SSR in the power system.

Power System Interconnection

Interconnection of power systems is becoming increasingly widespread as part of power exchange between countries as well as regions within countries in many parts of the world. There are numerous examples of interconnection of remotely separated regions within one country. Such are found in the Nordic countries, Argentina and Brazil. In cases of long distance AC transmission, as in interconnected power systems, care has to be taken for safeguarding of synchronism as well as stable system voltages, particularly in conjunction with system faults. With series compensation, bulk AC power transmission over distances of more than 1,000 km are a reality today and has been used in Brazil northsouth interconnection. With the advent of TCSC, further potential as well as flexibility is added to AC power transmission.

APPLICATION IN DEREGULATED ENVIRONMENT

Apart from its traditional application for voltage control, power flow control and enhancing steady state and dynamic limits, FACTS controllers are finding new applications in the present deregulated environment. One of the applications is in controlling the “parallel flow” or “loop flow”. Loop flow results in involuntary reduction in transmission capacity that may belong to some other utility and hence foreclose beneficial transactions through that line. Utilities can also make use of FACTS controllers in their tie lines, either to shield it from the neighbouring effects, such as wheeling transactions or to participate in such transaction. FACTS devices can also be implemented to ensure the economy in operation by placing it in a suitable line such that least cost generators can be dispatched more. It can also be used to reduce the losses in the system. Yet, another application is to use FACTS to relieve the congestion in the system. FACTS devices can be strategically placed such that congestion cost is reduced, curtailment is decreased and price volatility due to congestion is minimized.

BENEFITS AND COSTS

The benefits from the use of FACTS devices are many, however, not all are tangible. Similarly, the cost of FACTS devices are also huge. The world second UPFC came into operation at the end of year 2004 in Keepco power system in Korea. It was the largest single procurement order ever placed by Keepco. From this, it is clear how expensive these technologies are. But, the cost has to computed against anticipated benefits. One of the reasons for low deployment of FACTS is because very little has been done to show their profitableness.

FACTS devices can save the system from potential threat of system collapse, which can have very serious consequences on other economic sector as well. It can help to avoid the wide spread blackout. The opportunity cost of FACTS controllers in these situations has to taken into consideration.

BENEFITS

Environmental Benefit

The construction of new transmission line has negative impact on the environment. FACTS devices help to distribute the electrical energy more economically through better utilization of existing installation there by reducing the need for additional transmission lines. For example, in Sweden, eight 400 kV systems run in parallel to transport electrical energy from the north to the south. Each of these transmission systems is equipped with FACTS. Studies have shown that four very little has been done to show their profitableness.

FACTS devices can save the system from potential threat of system collapse, which can have very serious consequences on other economic sector as well. It can help to avoid the wide spread blackout. The opportunity cost of FACTS controllers in these situations has to taken into consideration.

Increased Stability

Instabilities in power system are created due to long length of transmission lines, interconnected grid, changing system loads and line faults in the system. These instabilities results in reduced line flows or even line trip. FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of line trips.

Increased Quality of Supply

Modern industries require high quality of electricity supply including constant voltage and frequency, and no supply interruptions. Voltage dips, frequency variations or the loss of supply can lead to interruptions in manufacturing processes with high economic losses. FACTS devices can help to provide the required quality of supply.

Flexibility and Uptime

Unlike new overhead transmission lines that take several years to construct, FACTS installation requires only 12 to 18 months. FACTS installation has the flexibility for future upgrades and requires small land area.

Financial Benefit

Financial benefit from FACTS devices comes from the additional sales due to increased transmission capability, additional wheeling charges due to increased transmission capability and due to delay in investment of high voltage transmission lines or even new power generation facilities. Also, in a deregulated market, the improved stability in a power system substantially reduces the risk for forced outages, thus reducing risks of lost revenue and penalties from power contracts.additional 400 kV transmission systems would be necessary, if FACTS were not utilized on the existing systems.

Reduced Maintenance Cost

The overhead transmission lines need to be cleared from the surrounding environment (e.g. tree branches) from time to time. In comparison to this, the FACTS maintenance cost is very minimum. In addition, as the number of transmission line increases, the probability of fault occurring in a line is also high. So, by utilizing the transmission systems optimally with the use of FACTS, the total number of line fault is minimized, thus reducing the maintenance costs.

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 4 [19]. 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.

Table 4: 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

CHAPTER-5

ISSUES

High cost and high losses, appropriate size and setting, location and procurement availability are some major issues with the use of FACTS controllers. Even with the long history of development, proven technology and long list of benefits, FACTS controllers are not yet widely deployed because of the high cost as compared to the conventional counterpart. The procurement availability of FACTS controllers is also a major issue. Market for SVC is widely developed and can be procured competitively. While, very limited competition exists regarding the procurement of TCSC and STATCOM. For the case of UPFC, it is more likely that there will be no competition at all. Another important concern is the losses, which increase with higher loading and FACTS devices produce more loss than the conventional ones. So, more effort is needed in the development of semiconductor switches that are fast and, at the same time, have low switching and conduction losses. Size of FACTS controllers also bears significance, since cost increases proportionally with the size. Similarly appropriate setting and location are important to obtain the desired performance. These are to be addressed during the planning stage of the FACTS project. As the number of FACTS controllers increases in the power system, the interactions among the controllers itself will be a serious concern that requires separate in-depth study.

CHAPTER-6

SELECTED CASE STUDIES

SVC in Thailand

The power system in Thailand during 1990s was undergoing strong expansion. A weak part of the bulk system was a tie-line linking major generation located in the central region with the load in the south. The length of this interconnection is about 700 km. Transient stability was a limiting factor for power transmission of this interconnection. Therefore, an SVC rated 50 MVAr inductive to 300 MVAr capacitive at 230 kV, was installed in 1994 at Bang Saphan substation, located midway along the interconnection. The purpose of the SVC is consequently to increase the transient stability, thereby increasing the power transmission capability of the system by a considerable amount. At the same time the SVC provides continuous voltage control under various operating conditions of the system. The SVC at Bang Saphan has enabled a considerable increase of the active power transmission capability of the power corridor to the south. Without the SVC, the power transmission capacity was limited to below 200 MW due to transient stability limitations of the tie-line. With the SVC in operation, the power transmission capacity has been raised to well over 300 MW, representing an improvement of power transmission capacity by more than 50% over existing lines.

TCSC in Brazil North-South

Interconnection

An example of AC interconnection of separate power systems within one country is found in Brazil. There are two main power systems in the country which were previously not interconnected, the North System and the South System. The system was connected with 500 kV AC line of 1,000 km long line and series compensated in several places.

The TCSC is located at the Imperatriz substation and Sarra de Mesa, which are the terminal points of the interconnection. The task of TCSC is to damp lowfrequency inter-area power oscillations between the power systems on either side of the inter-connection. These oscillations (0.2 Hz) would otherwise constitute a hazard to power system stability.

Statcom at SDG&E Talega Substation

The STATCOM installed in the SDG&E system at the Talega 138 kV substation is being applied to relieve transmission system constraints in the area through dynamic var control during peak load conditions. It is operating as a STATCOM with a rated dynamic reactive capacity of ± 100 MVAr. The main objectives of the Talega STATCOM are to regulate and control the 138 kV AC system voltage, to give dynamic reactive power support following system contingencies, and to provide high reliability with redundant parallel converter design and modular construction and operational flexibility through auto-reconfiguration design.

UPFC at AEP INEZ Substation

The first UPFC (± 320 MVA) was commissioned in 1998 at America Electric Power (AEP) Inez substation. At that time, the Inez load area has power demand of around 2,000 MW and was served by long heavily loaded 138 kV transmission lines. During normal power delivery, there was very small voltage stability margin for system contingencies. Single contingency outages in the area will adversely affect the underlying 138 kV system, and, in certain cases, a second contingency would be intolerable, resulting in a wide-area blackout. UPFC was installed at Inez substation to provide reliable power supply to the Inez area with effective voltage support and added real power supply facilities. More than 100 MW increase in power transfer, excellent voltage support at the Inez bus and reduction in real power loss by more than 24 MW was achieved with this installation.

CONCLUSIONS

With the history of more than three decades and widespread research and development, FACTS controllers are now considered a proven and mature technology. The operational flexibility and controllability that FACTS has to offer will be one of the most important tools for the system operator in the changing utility environment. In view of the various power system limits, FACTS provides the most reliable and efficient solution. The high initial cost has been the barrier to its deployment, which highlight the need to device proper tools and methods for quantifying the benefits that can be derived from use of FACTS.

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