Facts about Flexible AC Transmission Systems (FACTS) Controllers: Practical Installations and Benefits

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ABSTRACT
As a result of FACTS controllers' actual installations, advantages and utility applications, this paper provides a wide range of information. Detailed details on the development of these devices and the first utility installation/demonstration of FACTS devices are provided. Then, a thorough list of important FACTS installations across the globe is shown. Additionally, the article examines how these gadgets might benefit the user and how much they will cost. Various FACTS devices may be used in a deregulated market, according to the report. The FACTS controllers are likewise the subject of discussion. Advanced FACTS controllers have higher losses than their traditional counterparts, and thus must be taken into consideration when designing future power systems. FACTS controller examples and analysis are provided for each major controller in the study.

INTRODUCTION

Static limits and dynamic limits are two classifications for the limitations of the AC transmission system [1-3]. As a result of these built-in restrictions, transmission resources aren't being used to their full potential. Many of the issues were traditionally addressed using fixed or mechanically switched shunt and series capacitors, reactors, and synchronous generators. However, there are limitations on how these traditional gadgets may be used. Efforts to meet expectations were unsuccessful. Mechanical component wear and reaction time were the root causes of the issues. Solid state devices with quick reaction capabilities were in growing demand as an alternative technology. Overhead transmission line building permits and right-of-way were difficult to get because of the global reorganisation of electric companies, increased environmental and efficiency rules, and the difficulty of obtaining these permits and rights of way [4]. Since then, a new class of power electronics devices called as Flexible AC Transmission Systems (FACTS) controllers has emerged thanks to the discovery of the Thyristor switch (a semiconductor device). As high-power semiconductor devices advanced quickly [1-3], they enabled the transition from traditional Thyristor-based FACTS controllers to the current, ultramodern versions based on voltage source converters. Controllers of FACTS have

since the 1970s, when the first utility demonstration of the first FACTS family, the Static Var Compensator (SVC), was completed, has been used in utilities across the globe. A lot of time and energy has been devoted to the study and creation of FACTS controllers since then.

HISTORY OF DEVELOPMENT AND STATUS

STATIC VAR COMPENSATOR

The Static Var Compensator is a rudimentary FACTS controller from the first generation. The Electric Power Research Institute (EPRI) first introduced this technology to the market almost a quarter of a century ago. With this compensator, you may dynamically compensate for shunt effects by manipulating the reactor and/or the shunt capacitor bank through a fast-thyristor switch. A total of more than 800 SVCs have been deployed across the globe, in utility and industrial settings (most notably in electric arc furnace and rolling mills). Since its inception, SVCs have been used by utilities in undeveloped nations as well. Despite being a pioneer in the deployment of SVC, ABB only provided 55% of the total installations, with 13% of those installations taking place in the Asia-Pacific region. In 1974, General Electric (GE) established the world's first demonstration of SVC for utility use and marketed it [1].

Voltage control got more challenging in the UK after deregulation in 1990. The UK deployed relocatable SVC in order to deal with the uncertainty of the future and the ever-changing power system conditions (RSV). The

NGC (National Grid Company) system currently has 12 RSVC (60 MVAr each) in operation [5].

A SERIES CAPACITOR WITH A THYRISTOR IN CONTROL

In the first generation of FACTS devices, a capacitor bank is controlled by silicon-controlled rectifiers through a thyristor-controlled series capacitor (TCSC). TCSC enables utilities to move more electricity over a single line. ABB designed and implemented the world's first three-phase TCSC at Kayenta substation, Arizona, in 1992, which increased the transmission line's capacity by over 30 percent. Seven TCSCs have been set up throughout the globe by the end of 2004. Three TCSCs were established in Asia, two in China and one in India, placing Asia to the forefront of the latest FACTS technology on the continent. Table 1 lists all of the TCSCs that had been put into service as of December 2004 across the globe.

Static Synchronous Compensation (SSC) device

FACTS controllers that use STATCOMs (Static Synchronous Compensator) have a potential future use. Some of STATCOM's benefits are its tiny size, quick reaction time, and lack of harmonic pollution. It was the world's very first business enterprise.

Japan's Inuyama substation was the first to use Mitsubishi Electric Power Products' STATCOM (80 MVA, 154 kV) in 1991. Throughout 20 STATCOMs are now in use around the globe. Some of the most important utility-scale STATCOMs are included in Table 2.

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

STATIC SERIES SYNCHRONOUS COMPENSATOR

Complementary second-generation FACTS controller, the Static Series Synchronous Compensator (SSSC), basically a series version of STATCOM. SSSC has failed to establish itself as an independent controller in the marketplace. An all-in-one power flow regulator.

UNIFIED POWER FLOW CONTROLLER

Unified Power Flow Controller (UPFC) is the third generation of FACTS, which combines the STATCOM and SSSC into a single device with a common control framework (UPFC). Real and reactive power flow may be separately controlled using this device. The Inez substation of American Electric is home to the first utility demonstration of a UPFC.

1998 was a year of power. The Gangjin substation in South Korea is now undergoing construction of an 80 MVA UPFC. Two UPFCs are included in Table 3 for comparison purposes.

CONVERTIBLE STATIC COMPENSATOR

The "Convertible Static Compensators (CSC)" are the most current advancement in the area of FACTS controllers. Full flexibility is provided by being able to link CSC-converters in either series or shunt mode, as well as the ability to connect them in shunt/series Interline Power-Flow Controllers (IPFC) with two lines. New York Power Authority's Marcy 345 kV substation has the world's first CSC, which can operate in 11 distinct control modes.

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

3. FACTS APPLICATION

FACTS controllers may be utilized for numerous applications to boost power system performance. One of the main benefits of employing FACTS controllers is that it may be utilized in all the three states of the power system, namely: (1) Steady state, (2) Transient and (3) Post transient steady state. However, the traditional devices find limited applicability under system transient or contingency state.

STEADY STATE APPLICATION

Various steady state applications of FACTS controllers comprise voltage control (low and high), increase of thermal loading, post-contingency voltage control, loop flows control, decrease in short circuit level and power flow management. SVC and STATCOM may be used for voltage control whereas TCSC is better suitable for loop flow control and for power flow management.

CONGESTION MANAGEMENT

Congestion management is a key worry for Independent System Operator (ISO) in modern deregulated power markets since it may arbitrarily boost the prices and hampers the free electricity trade. FACTS devices like TCSC, TCPAR (Thyristor Controlled Phase Angle Regulator) and UPFC may assist to alleviate congestion, smoothen locational marginal pricing (LMP) and to promote the social welfare by shifting electricity from crowded interface to under used lines [7-8].

ATC IMPROVEMENT

In many deregulated market, the power transaction between buyer and seller is authorized based on computation of ATC. Low ATC means that the network is unable to accept new transaction and so does not foster free competition. FACTS controllers like TCSC, TCPAR and UPFC may assist to enhance ATC by enabling 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 regulation is well recognized [11-13].

LOADING MARGIN IMPROVEMENT

Several blackouts in numerous regions of the globe occurred mostly due to voltage failure at the highest loadability point. Series and shunt compensations are frequently employed to boost the maximum transmission capacities of power networks. The latest progress in FACTS controllers have enabled them to be employed more effectively for enhancing the loading margin in the system [14-15].

POWER FLOW BALANCING AND CONTROL

FACTS controllers, notably TCSC, SSSC and UPFC, allow the load flow on parallel circuits and various voltage levels to be maximized and managed, with a minimum of power wheeling, the greatest possible usage of the lines, and a lowering 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 augmentation. One of the most essential skills required of FACTS applications is to be able to lessen the effect of the main disturbance. The effect reduction for contingencies may be performed with dynamic voltage support (STATCOM), dynamic flow control (TCSC) or both with the usage of UPFC.

TRANSIENT STABILITY ENHANCEMENT

Transient instability is induced by big disturbances such as tripping of a main transmission line or a generator and the issue may be observed from the initial swing of the angle. FACTS devices can fix the issue by providing quick and rapid reaction during the initial swing to manage voltage and power flow in the system [16].

OSCILLATION DAMPING

Electromechanical oscillations have been seen in many power systems globally and may lead to partial power outage if not managed. Initially, power system stabilizer (PSS) is utilized for oscillation damping in power system. Now this function may be more efficiently handled by suitable placement and setup of SVC, STATCOM and TCSC [17-18].

DYNAMIC VOLTAGE CONTROL

Shunt FACTS controllers like SVC and STATCOM as well as UPFC may be applied for dynamic management of voltage during system contingency and prevent the system from voltage collapse and blackout. Abolition of SSR Under some unfavourable circumstances, the phenomenon of subsynchronous resonance (SSR) may be linked to series compensation. Because TCSC's dynamic properties are so dramatically different from normal series capacitors, they are employed in Stöde, Sweden, to eliminate SSR in the power supply.

CONNECTION OF THE POWER SYSTEM

Power exchange across nations and regions within countries is becoming more common as a result of interconnection of power networks. Within a single nation, there are countless instances of interconnectedness between areas that are physically separated. The Nordic nations, as well as Argentina and Brazil, all have these. Accurate synchronisation and steady system voltages must be ensured in the event of long-distance AC transmission as well as linked power systems. Power transmission across long distances of more than 1,000 kilometres is now a possibility thanks to the application of series compensation. With the introduction of TCSC, AC power transmission has more potential and flexibility. In an unregulated environment, it may be used.

Deregulation has given rise to new uses for FACTS controllers, including voltage management, power flow control, and increasing steady state and dynamic limitations. It is used to govern "parallel flow" or "loop flow," among other things. An unintentional decrease in transmission capacity that may otherwise benefit another utility is caused by loop flow. FACTS controllers may also be used by utilities in their tie lines, either to protect them from the impacts of their surroundings, such as wheeling transactions, or to take part in such transactions themselves.. The most cost-effective generators may be sent more often with the help of FACTS devices, which can be used to assure operating efficiency. Using it to cut down on systemic losses is another option. In yet another use, FACTS may be used to alleviate system congestion. Strategically located FACTS devices may reduce congestion costs, curtailment, and price volatility caused with congestion.

EFFECTIVENESS AND COST

There are several advantages to using FACTS devices, but not all of them can be seen. FACTS devices, on the other hand, are prohibitively expensive. When Keepco's power system went into service at the end of 2004, the second-largest UPFC in the world was up and running. Keepco has never made a single purchase order with such heft before. In light of this, it is evident that these technologies are very costly. However, the expense must be weighed against the projected advantages in order to make an informed decision. Low FACTS deployment is due to a number of factors,There has been relatively little done to demonstrate their profitability. Devices like FACTS can keep the system from going down, which would have disastrous ramifications for the rest of the economy. It may be of use in preventing a widespread blackout. It is important to take into account the FACTS controller's opportunity cost in these scenarios.

BENEFITS TO THE ENVIRONMENT

There are environmental consequences to building a new power transmission line. To reduce the need for new transmission lines, FACTS devices assist to distribute electrical energy more efficiently by making greater use of existing infrastructure. There are eight 400 kV lines running from the north to the south of Sweden, for example. FACTS is present in each of these transmissions. According to the research, four extra 400 kV transmission lines would be needed if FACTS was not implemented on the current systems.. Stability has been increased.

Long transmission lines, linked grids, shifting system loads, and line faults all contribute to power system instability. Due to the instabilities in the system, line flows are limited or the line may trip altogether. Transmission systems are stabilised by FACTS devices, which boost transfer capacity while reducing the likelihood of line trips. Quality of supply has been improved.

Modern manufacturing processes need a reliable, high-quality electrical supply with continuous voltage and frequency. It is possible for industrial operations to be halted due to voltage dips, frequency fluctuations or the lack of supply. Supply may be improved by using FACTS devices.

UPTIME AND FLEXIBILITY

It takes 12 to 18 months to deploy FACTS, compared to new overhead transmission lines that might take several years. Using FACTS allows for future updates while taking up little space.

INCOME INCREASE

In addition to the higher sales, greater wheeling costs, and delays in the installation of high voltage transmission lines or even new power production facilities, FACTS devices have a financial advantage. Forced outages are less likely in a deregulated market, thanks to a more stable electricity infrastructure, which means less money is lost and fines are less severe.

COST REDUCTION IN MAINTENANCE

The surrounding environment (such as tree branches) must be periodically removed from the overhead transmission wires. As a result, the expense of FACTS upkeep is negligible. As the number of transmission lines grows, the likelihood of a line fault also rises. As a result, maintenance costs are reduced by using FACTS to maximise the usage of transmission systems, which reduces the number of line faults. COSTS

Due to the high cost of the controllers, FACTS controllers are not widely used. Various conventional devices and FACTS controllers are compared in Table 4 [19] in terms of their average cost per kVar output. The cost per kVar of FACTS controllers falls with increasing capacity, on the other hand. The overall cost of the FACTS controllers also relies on the size of the fixed and controllable parts. Only half of the entire FACTS project cost is accounted for by the purchase of FACTS equipment. About half of the total cost of the FACTS project is allocated to other expenses, such as civil construction, equipment installation and commissioning, insurance, engineering and project management.

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

5. ISSUES

With the usage of FACTS controllers, there are a number of fundamental difficulties that need to be overcome. The expensive cost of FACTS controllers compared to the traditional equivalent means that despite their lengthy history of research, established technology, and extensive list of advantages, they are not yet widely employed.

Another big concern is the scarcity of FACTS controllers for purchase. SVC is commonly available and may be purchased at a reasonable price. Despite this, the procurement of TCSC and STATCOM is subject to a very limited amount of competition. There's a good chance there won't be any competition at all for UPFC. Another key issue is the rise in losses with increased loads, because FACTS devices create larger losses than traditional ones. The development of rapid semiconductor switches with minimal switching and conduction losses will need additional work. Due to rising costs, the size of FACTS controllers is an important consideration. Setting and location are equally critical in achieving the intended result. These are some of the things must be considered throughout the FACTS project's preliminary design stages. If there are more and more FACTS controllers in a power system, the interactions between the controllers themselves will become a major issue that demands more investigation.

6. CASE STUDIES Selected

In Thailand, SVC

During the 1990s, Thailand's political system underwent rapid modernization. The bulk system's weakest link was a connection between the centre region's large generation and the southern region's load. This 700-kilometer-long link connects the two continents. This interconnection's power transmission was hampered by its inability to maintain transient stability. Bang Saphan substation, situated about halfway along the interconnection, has an SVC constructed in 1994, which was rated for inductive to capacitive power ranges from 50 MVAr to 300 MVAr. Transient stability must be improved in order for the system's power transmission capacity to be significantly increased by using the SVC. Additionally, the SVC maintains constant voltage management in a wide range of system operating situations. Significantly more electricity can be sent to the south thanks to Bang Saphan's SVC (Southern Voltage Corridor). As a result, without the SVC, power transmission capacity would have been restricted to below 200 MW. More than half of the capacity boost over existing lines was achieved with the SVC, which now transmits electricity at well over 300 megawatts (MW).

A NORTH-SOUTH TCSC CONNECTION IN BOLIVIA

Brazil serves as an example of a country's several power systems being connected through alternating current (AC). Until recently, the country's two major electricity networks (the North and South systems) were not integrated. It was linked to a 500 kV AC cable approximately 1,000 kilometres long and corrected at many points.

These two connectivity locations, Imperatriz and Sarra de Mesa, are where the TCSC is based. Power oscillations between power systems on either side of an interconnection are dampened by TCSC. These 0.2 Hz oscillations would otherwise pose a risk to the stability of the power grid.

TALEGA SUBSTATION STATCOM

Transmission system restrictions in the Talega 138kV substation region are alleviated by dynamic var control applied to the STATCOM installed in the SDG&E system. Is running as a STATCOM with around 100 MVAr's dynamic reactive capacity. In order to regulate and control the 138 kV AC system voltage, to provide 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, the Talega STATCOM is designed.

STATION OF AEP INEZ UNDER UPFC CONTROL

In 1998, the first UPFC (320 MVA) was installed at the Inez substation of America Electric Power (AEP). Transmission lines serving Inez's power needs at the time had extensive, heavily-trafficked 138 kV conductors. In normal operation, the voltage stability margin for system contingencies was quite limited. When there are many contingency outages in a region, it might lead to a wide-area blackout if there are more than one outage in the same location. Real power supply facilities were added as well as dependable power supply at the Inez substation by installing UPFC. Power transfer was significantly increased, the voltage support at the Inez bus was exceptional, and actual power loss was reduced by more than 24 MW as result..

7. CONCLUSIONS

It is now widely accepted that FACTS controllers are a proven and mature technology after more than three decades of extensive study and development. System operators will greatly benefit from the operational flexibility and controllability that FACTS can provide in the rapidly changing utility landscape. FACTS is the most dependable and efficient option in light of the numerous limitations of the power system. As a result of the high initial cost, suitable tools and procedures are needed to quantify the advantages that may be gained through the usage of FACTS.

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