

USE OF FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS (FACTS) TO IMPROVE THE POWER FLOW CONTROL IN THE NIGERIA TRANSMISSION NETWORK

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ABSTRACT

This paper gives an overview of the Nigeria power transmission network with its associated mode of compensation as it relates to voltage drops and power losses. It also highlights the use and benefits to be derived from FACTS devices over conventional control devices employed in the present network in Nigeria. The study revealed that reactors, capacitors and tap changers used mainly in the Nigeria power network are sluggish and mechanical controlled and do not satisfy rapid changes in transmission network parameters. It identified areas in the network with low voltages and high power losses where FACTS devices can be injected in the Nigeria 330KV lines to increase transmission capabilities and boost power output to the national grid with a view to improving efficiency and reliability of power supply to consumers.

KEYWORDS: FACTS, Transmission, Power Flow, Compensation, Power Loss, Voltage drop, UPFC.

INTRODUCTION

The developing of interest in tools for power flow control in a power system has increased significantly during the last 10 years. Demand for research in this field is motivated by rapid transformations in both technology and organization of the power system industry. [1] Among the main requirements for such tools is the need to precisely satisfy in a short period of time the demand conditions for electrical energy supply. Deregulation in the power industry has led to an increasing number of competing companies, which implies a need for power flow to be controlled flexibly and locally, sometimes even at neighbourhood level. These requirements cannot be fulfilled by traditional electrical energy distribution networks, in particular because of sluggishness.

The concept of Flexible AC Transmission Systems (FACTS) was introduced by Hingorani in 1988 [1] through the Electric Power Research Institute (EPRI) representing the collaborative Research and Development (R & D) of the US Power utilities in Palo Alto, California. FACTS is defined by Institution of Electrical and Electronic Engineering (IEEE) as "Alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability." [2, 3]

Flexible power control and high dynamics can be achieved by applying solid-state power electronic converters. The significance of the power electronics and other static controllers is that they have high speed response and there is no limit to the number of operations. Like a transistor leads to a wide variety of processors, power electronic devices such as thyristors lead to a variety of FACTS Controllers and HVDC converters. These Controllers can dynamically control line impedance, line voltage, active power flow and

reactive power flow. A major unique feature of FACTS devices is their ability to absorb or supply reactive power and when storage becomes economically viable they can supply and absorb active power as well.

The FACTS technology offers power utilities the ability to control power flows on their transmission routes and allow secure loading of transmission lines to their full thermal capacity. It also offers great ability to transfer power between controlled areas, prevents cascading outages by limiting the effects of faults and equipment failures and damps systems oscillations. However, FACTS do not eradicate the need for additional transmission lines or upgrading of existing lines where thermal limits have been reached or where evaluation of losses added to the cost of FACTS shows that the new line or upgrading of existing line is the optimal solution. The objective of this paper is to examine the mode of compensation in the Nigeria power system and give insight into FACTS devices with a view to explore the usage in the Nigeria power system

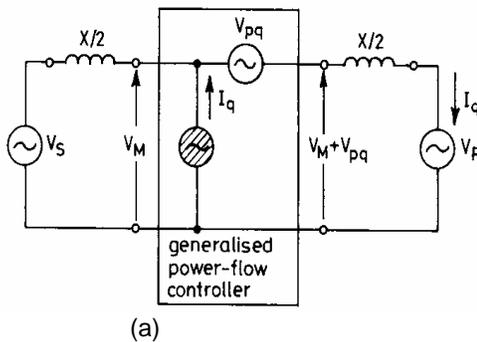
CONTROL OF AC POWER

The control of AC power in real time is very necessary since power flow is a function of the transmission line impedance, magnitude of the sending and receiving end voltages and the phase angle between these voltages. As the power transfer grows, the power system becomes increasingly more complex to operate and the system can become insecure when large power flows through with inadequate control and inability to utilize the full potential of transmission interconnections.

Before now, most power systems, by and large were mechanically controlled. All the electronics and high speed communications are at ground level, but at the high voltage end where the final action is taken, the devices are mechanical with little high speed control.

Control cannot be initiated frequently because machines tend to wear out very quickly compared with static devices. In effect, from the dynamic as well as steady state point of view, the system is really uncontrolled.

However, since Power flow over an AC line is a function of phase angle, line end voltages and line impedance and since there is no high speed control over any of these parameters, the operators can arrive at the required steady state power flow, while maintaining voltages and phase angles within safe tolerable limits, that is well below the peak stability limits of the power system. This is done through the use of generation scheduling, the occasional changing of power transformer taps and the switching of shunt reactors and capacitors. The consequences of this lack of fast, reliable control are stability problems, power flowing through routes other than the intended lines, the inability to fully utilize the transmission resources to their thermal and/or economic limits, undesirable VAR flows, higher losses, high or low voltages, cascade tripping and long restoration times. We have been brought up to think that these are inherent problems of the power systems and that AC transmission could not be controlled fast enough to handle dynamic system conditions. [4]



Transmission lines were thus designed with fixed or mechanically switched series and shunt reactive compensation, minimized voltage regulating and phase shifting transformer tap changers to optimize line impedance, minimize voltage variation and control power under steady-state or slowly changing load conditions.

The dynamic system problems were usually handled by over design, i.e. designing transmission lines with generous stability margins to recover from anticipated operating contingencies caused by faults, line and generator outages, and equipment failures, resulting in under utilization of transmission systems.

BASIC RELATIONSHIPS FOR POWER-FLOW CONTROL

The basic concept of controlling power transmission in real time assumes that, means are available for rapidly changing those parameters of the power system which determines the power flow. To consider the possibilities for power-flow control, the basic power relationships for the simple two-machine model, is shown in Figure 1 [4, 5]

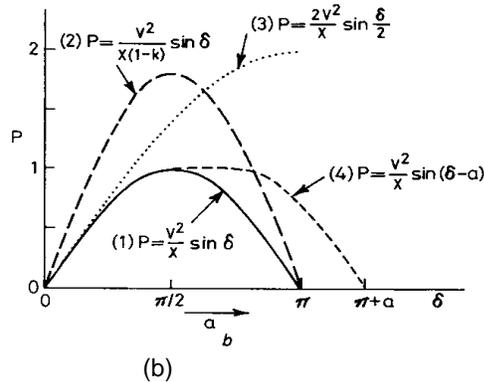


Figure 1: Basic power relationships for simple two-machine model.

Let the sending end voltage be V_s , receiving end V_r and impedance X with 2 sections and a generalized power flow controller with voltage source V_{pq} inserted in series with the line and a current source I_q , connected in shunt with the line at midpoint. Both the magnitude and the angle of voltage V_{pq} are freely variable, whereas only the magnitude of current I_q is variable; its phase angle is fixed at 90 degrees with respect to midpoint voltage V_M (which is assumed to be the reference phasor with zero phase angle).

The four classical cases of power transmission are as shown in figure 1b. These can be obtained by appropriately specifying V_{pq} and I_q in the generalized power flow controller shown in Fig.1 (a)

1. Without line compensation, assuming that both V_{pq} and I_q are zero,

$$P_1 = \frac{V^2}{X} \sin \delta \dots\dots\dots \text{Eq.1}$$

2. With series capacitive compensation, assuming that $I_q = 0$ and $V_{pq} = -jkX_L$, then

$$P_{(2)} = \frac{V^2}{X(1-k)} \sin \delta \dots\dots\dots \text{Eq.2}$$

3. With shunt compensation assume that $V_{pq} = 0$ and $I_q = -j(4V / X) [1] \cos (\delta/2)$, then

$$P_{(3)} = 2 \frac{V^2}{X} \sin \frac{\delta}{2} \dots\dots\dots \text{Eq.3}$$

4. With phase-angle control, assuming that $I_q = 0$ and $V_{pq} = \pm jV_M \tan \alpha = \pm jV_M \tan \alpha$,

$$P_{(4)} = \frac{V^2}{X} \sin(\delta - \alpha) \dots\dots\dots \text{Eq.4}$$

OVERVIEW OF NIGERIA POWER SYSTEM

.A critical study of the National Grid revealed that Nigeria’s generating plants sum up to 6200MW out of which 1920 MW is hydro and 4280 MW thermal – mainly gas fired[6]. The network has only one major loop system involving Benin – Ikeja West – Ayede – Oshogbo and Benin. Loops system provides alternative routes for power flow. The absence of loops accounts mainly for the weak and unreliable power system in the country. The pictorial view and the single line diagram of

the existing 330kV Nigerian transmission network are shown in figure 2.

According to Onohaebi [7], Power flow analysis of the transmission grid revealed that the existing condition of the Nigerian 330kV transmission is very unsatisfactory. The bus voltages at Kaduna, Kano, Jos and Gombe were found at the time of the investigation to be (298kV, 0.903pu), (247kV, 0.75pu), (251kV, 0.76pu) and (217kV, 0.66pu) respectively. These voltages are ridiculously low for the system to perform efficiently. The power losses on some of the lines were high, with Shiroro-Jebba line recording the highest value

of 12.77MW, with percentage loading of only 50.8%. The real power losses in the network under the existing condition amounted to 100.6 MW. The energy loss for 2005 due to 330kV transmission lines alone was found to be 337.5 GWH amounting to over two billion, six hundred thousand naira. [8]

Contingency analysis carried out on the network to verify the effect of losing any line in the system also indicates a total of 208 violations.[9] There is no line in the network that does not result in at least 2 violations. Increase or decrease in loading conditions further forces more buses to be out of tolerance.

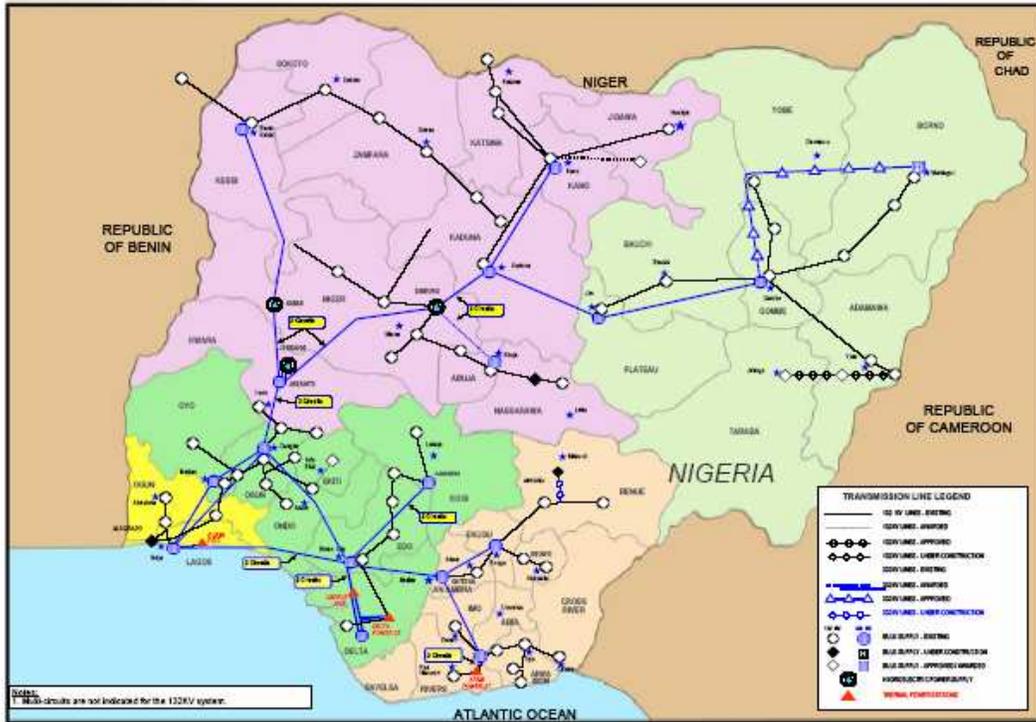


Fig. 2: Pictorial view of the existing 330kV Nigerian Transmission Network (Source: 10)

MODES OF COMPENSATION IN THE NIGERIA POWER SYSTEM

The Nigerian Power System relied heavily on load shedding during heavy loads as a result of low voltages, leading to low reliability of the system or interconnecting them with other lines instead of providing good compensating devices. The system uses conventional compensating devices like capacitors, reactors, tap changers, etc which are sluggish and mechanically controlled. Series Capacitors are inserted on long lines to reduce the impedance, thus reducing the voltage drop along the line and decreasing the amount of losses due to reactive power. The capacitors

increase the flow of power on the line on which they are inserted and reduce the power flow on other parallel lines. However, a major disadvantage of the series capacitor banks is that automatic protection devices must be installed to bypass high currents during fault conditions and to insert the capacitor banks after the fault clearing. The Nigeria power system lacks these automatic devices. Addition of series capacitors can also excite low frequency oscillations, a phenomenon called subsynchronous resonance, which can damage turbine-generator shafts. Figure 3 shows a series Compensated transmission system.

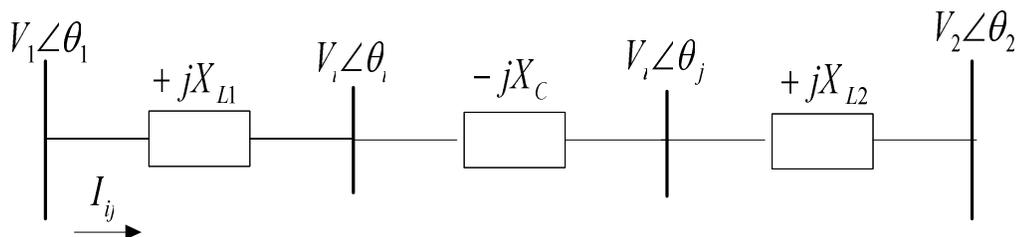


Fig. 3: A series Compensated transmission system

Shunt Capacitors are also used to deliver reactive power and increase transmission voltage during heavy load conditions. The addition of a shunt capacitor bank to a load bus corresponds to the addition of a negative reactive load, since a capacitor absorbs reactive power. Reactors are widely used in the Nigeria power system. They can be connected in series to reduce the power flowing through a line which otherwise would be overloaded and they also help to limit short circuit currents but increase voltage drops on the line, thus reducing power transfer capability. Shunt Reactors are installed at selected point along the 330kv and 132kv high voltage lines to absorb reactive power and reduce over-voltage during light load conditions. They also reduce transient over-voltages due to switching and lighting surges. However, they can reduce line

loadability if they are not removed under full-load conditions. Figure 4 shows a schematic diagram and an equivalent circuit for a compensated line section, where N_C is the amount of series capacitive compensation expressed in percent of the positive-sequence line impedance and N_L is the amount of shunt reactive compensation in percent of the positive sequence line admittance. Table 1 shows the locations and ratings of reactors installed in the 330 and 132kv in Nigeria. Tap changers are also presently used in the Nigeria system to increase line voltage and this has inherent problems associated with it. Figure 5 shows the front view of a 75MVAR located Benin 330kv transmission station. It was also observed that the use of FACTS devices to improve the performance of lines is not yet available in the Nigerian Power System.

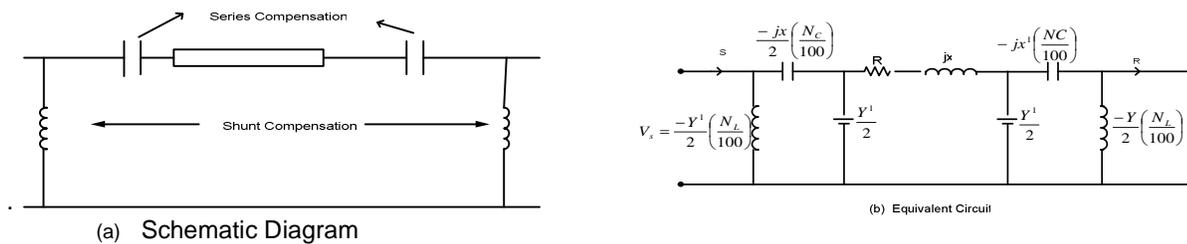


Fig. 4: Schematic diagram and Equivalent Circuit for a compensated line section

Table 1: PHCN REACTOR DATA (Source: 9)

STATION	REACTOR RATING	
STATION	MVAR	KV
Birin Kebbi	30	138
Jebba	75	330
	75	330
	75	330
Oshogbo	75	330
Ikeja West	75	330
Kaduna	30	138
	30	138
	75	330
Jos	75	330
Gombe	50	330
	50	330
	30	33
	30	33
Benin	75	330
Onitsha	30	138
Alaoji	30	33

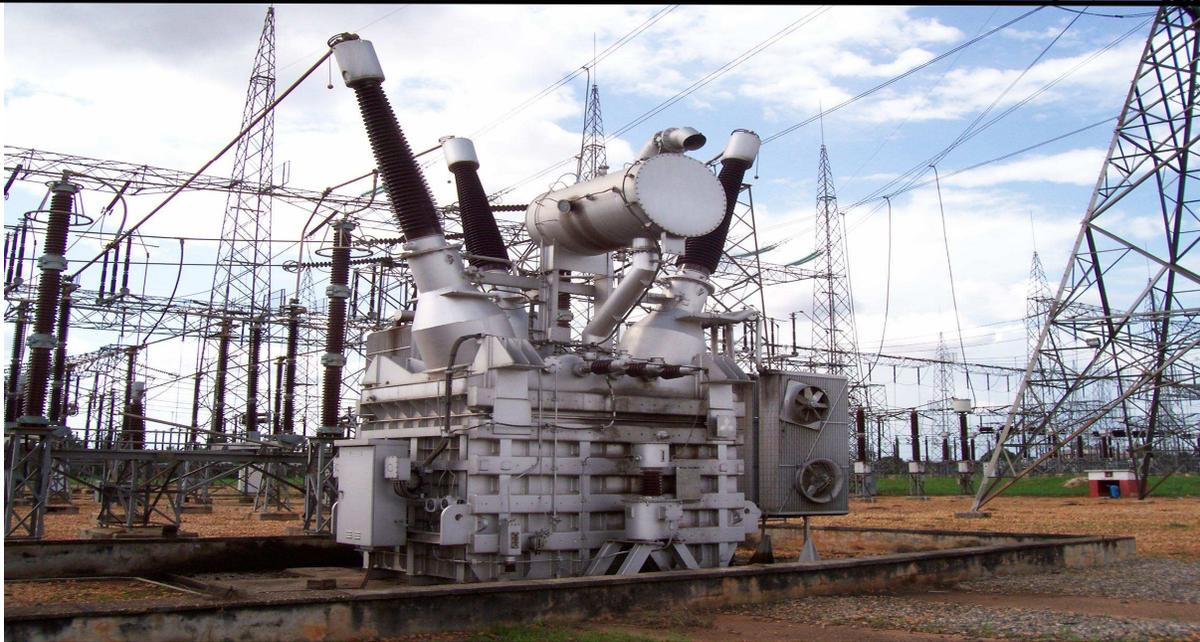


Figure 5: 75MVAR Reactor Located at Benin 330kV Transmission Station

VARIETY OF FACTS DEVICES USED IN TRANSMISSION NETWORK

FACTS devices can be conventional Thyristor controlled or Gate-Turn-off (GTO) Thyristor Controlled.

Power-flow controllers using conventional thyristors

Shunt-connected Static VAR compensator, composed of thyristor-switched capacitors (TSCs) and thyristor-controlled reactors (TCRs). With proper coordination of the capacitor switching and reactor control, the VAR output can be varied continuously between the capacitive and inductive ratings of the equipment. The compensator is normally operated to regulate the voltage of the transmission system at a selected terminal, often with an appropriate modulation option to provide damping if power oscillation is detected. Controllable Series Compensator can be Thyristor-Switched Capacitor where the degree of series compensation is controlled by increasing or decreasing the number of capacitor banks in series, Fixed Capacitor Thyristor Controlled Reactor where the degree of series compensation in the capacitive operative region is increased or decreased by varying the current in the TCR. Thyristor Controlled Phase Shifter provides quadrature voltage injection. The magnitude of the quadrature voltage injected could be varied continuously

by thyristor firing-angle control at the expense of harmonic generation. The thyristor-controlled phase-shifting transformer could be applied to regulate the transmission angle to maintain balance power flow in multiple transmission paths, or to control it so as to increase the transient and dynamic stabilities of the power system.

Gate-turn-off thyristor controlled compensators.

Recent advances in the high power solid-state switches such as Gate Turn off (GTO) Thyristors have led to the development of transmission controllers that provide controllability and flexibility for power transmission. These devices are all solid state power flow controllers using power switching converters. The unified power flow converter (UPFC) which was introduced in 1991 by Gyugiy [10] consists of series and shunt connected converters. The UPFC can provide the necessary functional flexibility for optimal power flow control. This approach allows the combine application of phase angle control with controlled series and shunt reactive compensation.

Table 2 [11] Shows the different types of FACTS and their areas of applications while **Table 3** shows the comparison between the conventional thyristor controlled and the unified power flow controller

Table 2: Types of FACTS and their areas of applications [12]

FACTS	AREAS OF APPLICATIONS
Static VAR Compensator (SVC)	Voltage control, VAR compensation, damping oscillations, transient and dynamic stability, voltage stability.
Static Synchronous Compensator (STATCOM without storage)	Voltage control, VAR Compensation, damping oscillations, voltage stability.
Static Synchronous Compensator (STATCOM with storage)	Voltage control, VAR Compensation, damping oscillations, transient and dynamic stability, voltage stability, AGC.
Thyristor Controlled Braking Resistor (TCBR)	Damping Oscillations, transient and dynamic stability.

Static Synchronous Series Compensator (SSSC without storage)	Current control, damping oscillations, transient and dynamic stability, voltage stability, fault current limiting.
Static Synchronous Series Compensator (SSSC with storage)	Current control, damping oscillations, transient and dynamic stability, voltage stability.
Thyristor Controlled Series Capacitor (TCSC)	Current control, damping oscillations, transient and dynamic stability, voltage stability, fault current limiting.
Thyristor Controlled Series Reactor (TCR)	Current control, damping oscillations, transient and dynamic stability, voltage stability, fault current limiting.
Thyristor Controlled Voltage Regulator (TCVR)	Reactive power control, voltage control, damping oscillations, transient and dynamic stability, voltage stability.
Thyristor Controlled Phase Shifting Transformer (TCPST or TCPR)	Active power control, damping oscillations, transient and dynamic stability, voltage stability.
Unified Power Flow (UPFC)	Active and reactive power control, voltage control, VAR compensation, damping oscillations, transient and dynamic stability, voltage stability, fault current limiting.

Table 3: Comparison between Conventional Thyristor-Controlled and Unified Power Flow-Controller

	Conventional Thyristor-Controlled	Unified Power Flow-Controller
a	Employs traditional system compensation using thyristors valves to replace mechanical switches	Uses solid-state voltage sources instead of switched capacitors and reactors or tapped changing transformer
b	Each scheme is devised to control a particular system parameter affecting power flow. Thus, static VAR compensator for reactive power and voltage control, CSC for line impedance and tap-changing transformer for phase shift	UPFC regulates or controls line impedance, voltage and phase angle via a single series voltage-source injection and generate controllable reactive power for independent shunt compensation.
c	They are custom-designed system with different manufacturing and installation requirements.	UPFC functions are provided by the same solid-state inverter. It is based on a single power electronic hardware building block, the voltage sourced inverter.
d	Large physical size relatively high overall cost dominated by none electronic components and labour. Thus, large labour are required for installation.	UPFC, apart from the coupling transformer, require no large storage components like capacitors and reactors. Thus, physical size is small and labour minimal. It is modular.
e	Require two totally different, independent equipment to control impedance and phase angle. The phase shifter.	UPFC can simultaneously or selectively provides series impedance compensation and phase angle control.
f	Cannot generate its own reactive power demand but have to be supplied from line or separate VAR source	UPFC generates internally all the reactive power required to accomplish the power flow by series voltage injection.
g	Require 'in phase' transformer windings with an independent thyristor arrangements.	Regulates voltage without additional hardware by direct, in-phase voltage injection.
h	In phase shifter and static VAR compensator, the VAR capacity of the compensation is dedicated for the supply of reactive power resulting from the series voltage injection.	Provides controllable shunt reactive compensation for the line independent of the reactive power demand of the series voltage injection.
i	Poor performance when used independently compared to UPFC	UPFC can be used independently as an advance static VAR compensator and controllable series compensator, and exhibit characteristics superior to their conventional controlled counterpart.
j	Conventional thyristor-controlled series compensator performs poorly compared to UPFC advanced controllable series compensator.	Advance controllable series compensator employs no series capacitor and thus can not cause synchronous resonance.

CASE STUDIES OF FACTS INSTALLATIONS AND THEIR EFFECTS ON THE POWER SYSTEM NETWORK IN USA

FACTS installations have been successfully implemented in many places of the world using thyristor-

controlled series capacitor, static synchronous compensator (STATCOM), unified power range (from full capacitive to full inductive) of shunt compensation, unified power flow controller (UPFC) including both shunt and series compensator, and convertible static

controller (CSC) providing a shunt device for voltage control and a series device for power management.^[1]

The installed FACTS controllers have provided new possibilities and unprecedented flexibility aiming at maximizing the utilization of transmission assets efficiently and reliably. FACTS technology has been successfully implemented at transmission locations in the United States. These FACTS controllers provide the right corrections for transmission voltage, line impedance, and phase angle at the right locations on the transmission system resulting in full utilization of transmission system allowing for more power flow and relieving transmission bottlenecks without building new lines. The Electric Power Research Institute (EPRI) sponsored a FACTS research program that includes software and hardware developments. The software program involves analytical and mathematical models for FACTS controllers. The models were included in EPRI digital simulation packages used in running application studies for utility members' power systems.

Some of the computed results of power transfer capability increases for three transmission systems in the United States include

- Transmission line in southwestern United States, boosting power flow from 300 MW to 400 MW (+33%)
- Ties between southern United States and Florida, boosting power flow from 3,400 MW to 4,100 MW (+21%)
- Ties between upstate New York and New York City, boosting power flow from 2,600 MW to 3,200 MW (+23%)

The Hardware program has also evolved in full-scale hardware demonstrations of FACTS controllers, which provide dynamic control of the power transfer parameters: line impedance, bus voltage, and phase angle. Figure 6 shows some of the stations in United States where FACTS have been successfully implemented as follows:

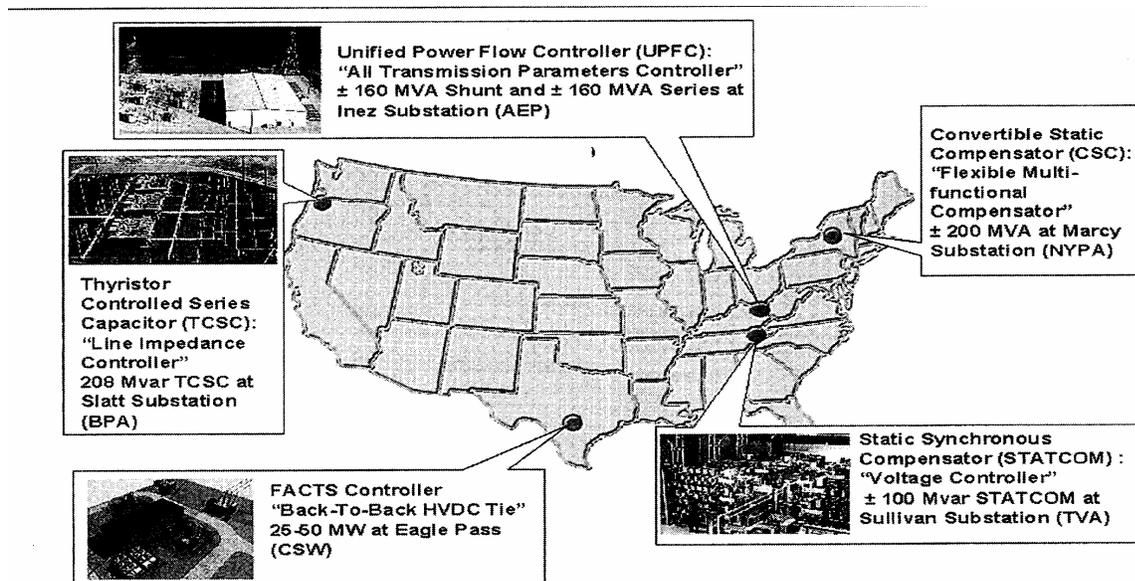


Figure 6: Types and Locations of FACTS Installations in the United States^[11]

(a) STATCOM AT Sullivan Substation

The Sullivan Substation lies on the TVA's service territory in northeastern Tennessee and is supplied by a 500 kV bulk power network and by four 161 kV lines that are interconnected through a 1,200MVA transformer bank. Seven distributors and one large industrial customer are served from this substation.

The Static Synchronous Compensator (STATCOM) regulates the 161 kV bus voltages during daily load increases to minimize the activation of the tap changing mechanism on the transformer bank, which interconnects the two power systems. The use of the STATCOM to regulate the bus voltage has resulted in reduction in the use of tap changer from about 250 times per month to about 2 to 5 times per month. Tap changing mechanisms are prone to failure, and the estimated cost of each failure is about \$1m^[13]. Nigeria power system still relies heavily on this highly inefficient tap changing facility. The Sullivan substation is also equipped with a mechanically switched 84 Mvar

capacitor banks to extend the effective range of the STATCOM from 184 Mvar capacitive to 100Mvar inductive. Without the STATCOM, TVA would be compelled either to install a second transformer bank at Sullivan or to construct a fifth 161 kV line into the area; both are costly alternatives. The STATCOM has allowed TVA to defer these expenditures.

(b) UPFC at Inez Substation

The Inez load area has a power demand of approximately 2,000 MW and is served by long, heavily loaded, 138 kV transmission lines. This means that, during normal power delivery, there is a very small voltage stability margin for system contingencies. Single contingency outage in the area will adversely affect the underlying 138kV system and, in certain cases, a second contingency would be intolerable, resulting in a wide-area blackout. A reliable power supply to the Inez area, therefore, requires effective voltage support and added real power supply facilities. System studies have

identified a reinforcement plan that includes among other things, the following system upgrades:

- Erection of a new double-circuit high-capacity 138kV transmission line from Big Sandy to the Inez substation.
- Installation of a FACTS controller to provide dynamic voltage support at the Inez substation and to ensure full utilization of the new high capacity transmission line. The UPFC satisfies all these needs, providing independent dynamic control of transmission voltage as well as real and reactive power flow.

The other benefits include:

- Dynamic support of voltage at the Inez substation to prevent voltage collapse under double transmission contingency conditions.
- Flexible, independent control of real and reactive power flow on the new high capacity (950MVA thermal rating) Big Sandy to Inez 138kV transmission line.
- Optimal utilization of the existing transmission system
- It enables transmission capacity for years of load growth
- Reduction of real power losses by more than 24MW, which is equivalent to a reduction of CO₂ emissions by about 85,000 tons per year
- The UPFC provides more than 100 MW increase in the power transfer and excellent voltage support at the Inez bus.

(c) CSC at Marcy Substation

The New York State (NYS) system, has two major interfaces, the "Total East" interface and the "Central East" interface. Currently, the transfer across these interfaces is limited to 6,150 MW and 2,880 MW, respectively. These limits are imposed by voltage collapse conditions and power system damping concerns, which could occur at critical contingencies. New York Power Authority (NYPA) and EPRI have conducted extensive studies to identify the means by which existing operational restrictions could be removed in order to increase power transfer capabilities while maintaining network reliability and providing flexibility to meet future uncertainties.

The conducted studies have resulted in the identification of a FACTS controller that could serve dual role by initial application as a shunt device, for voltage support in the short term, and as a series device for power flow management in the long term. Thus, the Convertible Static Compensator (CSC) was installed. The following benefits were derived from the installation of CSC:

- Increase upstate-to-downstate power transfer by 240MW,
- Relieve power transfer bottleneck
- Provide maximum utilization of NYS transmission system
- Improve voltage control
- Reduce system losses

THE WAY FORWARD FOR NIGERIA

Examination of the modes of compensation available in the Nigeria power system showed that Nigeria is still far behind in modern trends in the control

of power flow. The network is associated with low power generation, heavy voltage drops and power losses. A situation where about 44.5% [11] of sent-out generation results as power losses (technical and non technical) is very unhealthy for the system. Ways to reduce these losses and ensures high reliability of the network should be a major task of power system operators .The ability to conserve what is generated, boost and made it available for consumers can be enhanced greatly by the use of FACTS. If developed countries like USA with their high generation can still use FACTS to improve their transmission capability and reduce losses, Nigeria have no alternative but to urgently seek ways of install these devices to improve the efficiency and reliability of the network. The case studies with USA have shown that FACTS devices can help to improve power generation, supply and absorb reactive power as the need arises. The present state of Nigeria power system even when more generation stations are constructed will not bring the desired change if efficient and reliable means are not available to control the power flow. Transmission lines identified to record high voltage drops and power losses should be the starting point for the installations.

CONCLUSION

This paper reviewed the mode of compensation in the Nigeria power and revealed that conventional control devices are used in the Nigeria power network. This device which are mainly reactors, capacitors and tap changers are sluggish and mechanically controlled and do not satisfy modern power flow control capabilities. FACTS devices can be injected in various locations with low voltages and high power losses in the Nigeria 330KV/132KV lines to increase transmission capabilities and boost power output to the national grid.

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