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Analysis of Energy Controllers for Enhancement of Energy Flow

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***Abstract*—** The fast changing energy market has brought the new challenges in the field of transmission systems. Today's energy transmission networks are not designed for easy voltage flow in a deregulated market and steady state control problems as well as dynamic problem are the result. A new technology in this field, the flexible ac transmission system is gaining popularity in the world due to its enormous advantages. This paper gives an overview of its development; briefly describes its device and explains its effects. Furthermore, because of the tremendous influence on the system by the introduction of flexible ac transmission system, there is a great demand to improve the energy system analysis. Also, this paper present some aspects and direction needed to be studied.

***Keywords*—**Flexible AC Transmission System Devices, Inter-line Power Flow Controller, Static synchronous Series Compensator, Static Var Compensator, Transfer Capability, Thyristor Controlled Reactor.

I. INTRODUCTION

New socio economic conditions have fuelled the further growth of interconnection between neighboring utility systems to share energy with other regional pools and growing grid. The electric utility must run more rapidly to meet the heavily increasing demands of power. In the procedure of expanding and interconnecting of energy system, various problems arise. In the interconnected energy system, [1-3] the energy flow from the generator to the consumers is dependent on the location of the generation node, of the consumer nodes, and on the transmission paths available i.e. on the energy system topology and the characteristics of the lines involved, the result is transmission bottlenecks and unwanted parallel path or loop flows. In the large-scale energy system, the stability becomes more critical; several large area energy failures due to damaging of energy system stability resulted in enormous economic losses in the world. Power transfer capacity along a transmission corridor is limited by several factors such as thermal limit, steady state stability limit, transient stability limit and system damping. In certain situations a power system may have inadequate damping or even negative damping. A typical scenario of the magnitude of various limits is depicted graphically in Fig. 1. Flexible AC Transmission Systems offer a solution to these problems, and are now finding wide usage in power systems worldwide. On account of irregular distribution of the energy sources, [4-6] and the vast amount of transfer energy over long distance between the generation center and the load center, huge losses occur. Most of the controllers designed in the past were mechanical in nature. But mechanical controllers have numerous intrinsic problems. Many electronics controllers have been designed to supplement the potentially faulty mechanical controllers. These electronic controllers are all grouped in a category called flexible AC transmission controllers. Flexible AC Transmission System has all the capacity and operators need to meet the challenges presented by the fast changing energy market. This paper regards flexible ac transmission system as all modern electronic applications which can make impacts on the AC transmission in the large scale energy system and the scope of its application is thought to be the whole system, to contain generation, transmission and distribution parts, in which the transmission system is the key section.

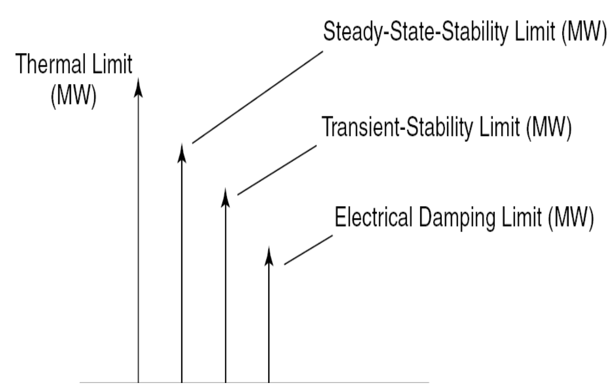


Fig .1 Different limits on power flow in transmission systems

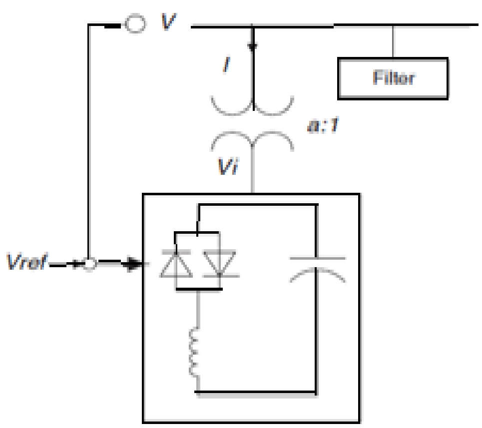
II. FLEXIBLE AC TRASMISSION SYSTEM

The term Flexible AC Transmission System covers all of the electronic based controllers in energy transmission. The main controllers are: Static shunts compensators, Static series compensators and combined compensators.

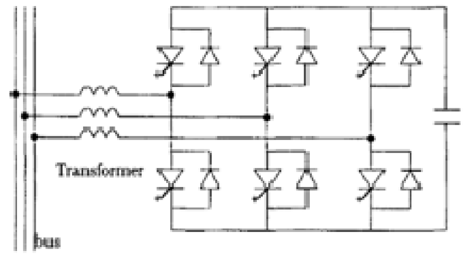
A. *Static Shunt Compensators:*

Shunt compensator is used to influence the natural characteristics of the transmission line to increase the steady-state transmittable energy and to control the voltage profile along the line. Static shunts compensators are: Static Var Compensators, and Static Synchronous compensators. The SVC is one of the frequently employed FACTS Controllers. It is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). Another most widely employed shunt controller, STATCOM is a controlled reactive power source. It provides desired reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a voltage source converter (VSC).

***a) Comparison of Shunt Compensators*:** SVC and STATCOM are very similar in their functional compensation capability, but the basic operating principles are fundamentally different. A STATCOM functions as a shunt-connected synchronous source whereas a SVC operates as a shunt-connected, controlled reactive admittance. This difference accounts for the STATCOM's superior functional characteristics, better performance, and greater application flexibility than those attainable with a SVC. In the linear operating range the characteristic and functional compensation capability of the STATCOM and the SVC are similar, the STATACOM is able to control its output current over the rated maximum capacitive or inductive range independently of AC system voltage , whereas the maximum attainable compensating current of the SVC decreases linearly with AC voltage .Thus , the STATCOM is more effective than the in providing voltage support under large system disturbances during which the voltage excursions would be well outside of the linear operating range of the compensator. The ability of the STATCOM to maintain full capacitive output current at low System voltage also makes it more effective than the SVC in improving the transient stability. The attainable response time and the bandwidth of the closed voltage regulation loop of the STATCOM are also



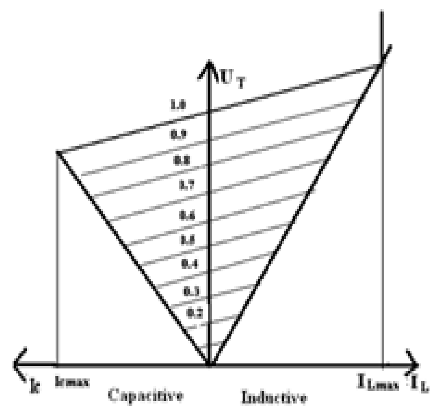
(a) SVC Controller



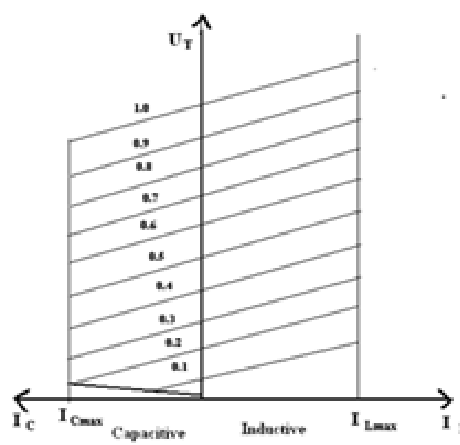
(b) STATCOM Controller

Fig.2 Basic Structure of Shunt Controllers

significantly better than those of the SVC. In situations where it is necessary to provide active power compensation the STATCOM is able to interface suitable energy storage (large capacitor, battery) from where it can draw active power at its DC terminal and deliver to as AC power to the system. On the other side, the SVC does not have this capability .



(a) Static Var Compensator



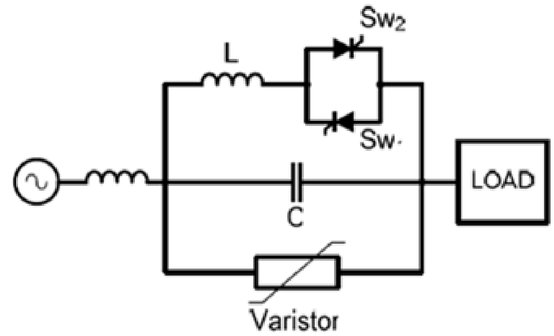
(b) Static Synchronous compensator

Fig.3 Characteristics of Shunt Compensators

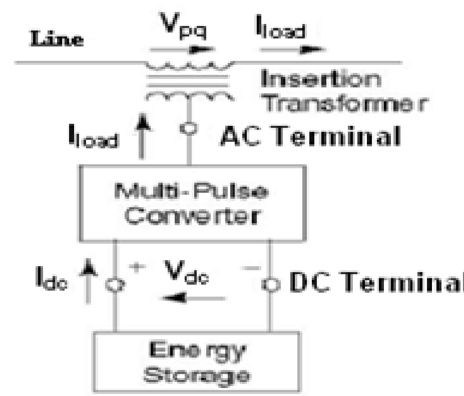
B. ***Static Series Compensators:***

The variable series compensation is highly effective in both controlling power flow in the line and in improving stability. With series compensation the overall effective series transmission impedance from the sending end to the receiving end can be arbitrarily decreased thereby influencing the power flow**.** This capability to control power flow can effectively be used to increase the transient stability limit and to provide power oscillation damping. Static Series compensators are: Thyristors-Switched series Capacitor, Thyristor controlled series Capacitor, Static Synchronous series compensator, and phase shifting transformers

a) Comparison of Series Compensators: The Static Synchronous series compensator is a voltage source type and the Thyristors-Switched series Capacitor, Thyristor- controlled series Capacitor, are variable impedance type series compensators .Resulting from the different structures there are essential differences in characteristics and features of these devices. The SSSC is capable of internally generating a controllable compensating voltage over an identical capacitive and inductive range independently of the magnitude of the line current .The compensating voltage of the GTO Thyristor-controlled series Capacitor and Thyristors-Switched series Capacitor over a given control range is proportional to the line current . The TCSC can maintain maximum compensating voltage with decreasing line current over a control range determined by the current boosting capability if the thyristor-controlled reactor. The Static Synchronous series compensator has the ability to interface with an external DC power supply to provide compensation for the line resistance by the injection of active power as well as for the line reactance by the injection of reactive power. The variable impedance type and can only provide reactive compensation .The Static Synchronous series compensator [6-10] with an energy storage increase the effectiveness of power oscillation damping by modulating the series reactive compensation to increase and decrease the transmitted power and by concurrently injecting an alternating virtual positive and negative real impedance to absorb and supply active power from the line in sympathy with the prevalent machine swings The impedance type compensators can damp power oscillation only by modulated reactive compensation affecting the transmitted power. Series reactive compensation can be highly effective in controlling power flow in the line and in improving the dynamic behavior of the power system. But certain problems related to the transmission angle cannot be handled by series compensation. For example, the prevailing transmission angle may not be compatible with the transmission requirements of a given line or it may vary with daily or seasonal systems loads over too large to maintain accepted power flow in some affected lines. To solve these problems, phase angle regulators (PAR) or phase shifting transformers (PST) are employed.



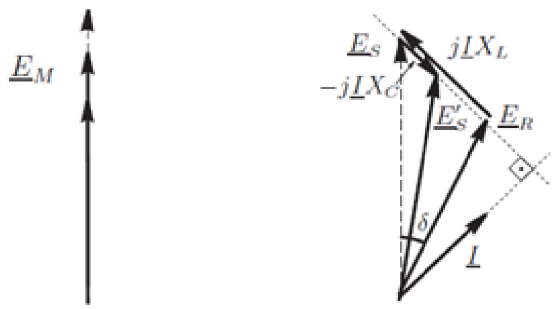
(a) TCSC Controller



(b) SSSC Controller

Fig .4 Basic Structures of Series Controllers

b) Comparison of Shunt and Series Compensators: The series-connected controllers impact the driving voltage and hence the current and power flow directly. Therefore, if the purpose of the application is to control the current/power flow and damp oscillations, the series controllers are several times more powerful than the shunt controllers. The shunt controllers are like current sources .They draw from or inject current into the line. Thus, shunt controllers are applied to control voltage at and around the point of connection through injection of reactive current. Because STATCOM's have the capability [10-16] to inject active as well as reactive current they are able to provide an even more effective voltage control and damping of voltage oscillations. This does not mean that the series controllers cannot be used for voltage control. Because the voltage fluctuations are largely a consequence of the voltage drop in series impedances of lines, transformers and generators, inserting a series compensator might be the most cost-effective way of improving the voltage profile. Nevertheless, a shunt controller is much more effective in maintaining a required voltage profile at a substation bus. That is because the shunt controller serves the bus node independently of the individual lines connected to the bus.



(a) (b)

Shunt Reactive Compensation Series Reactive Compensation

Fig.5 Voltage diagram of reactive series and shunt compensation

From the above consideration it can be followed that combination of series and shunt controllers can provide the best of both, i.e. an effective power/current flow and line voltage control. Capacitors and Reactors connected in Shunt with the transmission line provide shunt compensation. By controlling the current voltage magnitude at the point of connection can be regulated [Fig.5 (a)] Capacitors connected in series with the transmission line provide series compensation. The compensating effect results from the voltage drop across the series capacitors caused by the line current [Fig.5 (b)] The Power –Angle curve for different

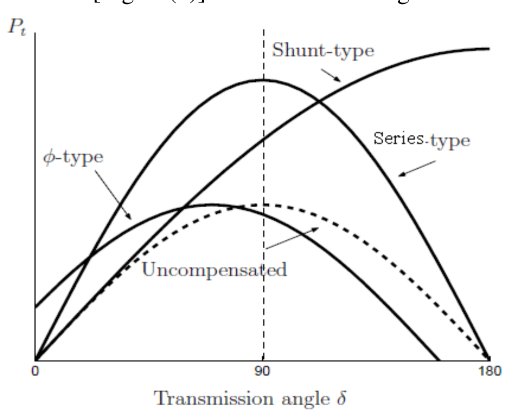


Fig. 6 Power –Angle curve for different controllers

controllers is shown in Fig.6. In shunt type and series type controllers the steady–state maximum is increased as compared to uncompensated system. Whereas in phase -angle control. Power –Angle curve is shifted to the left, permitting higher power flows for smaller transmission angles. However, the maximum transmittable power is independent of the transmission angle.

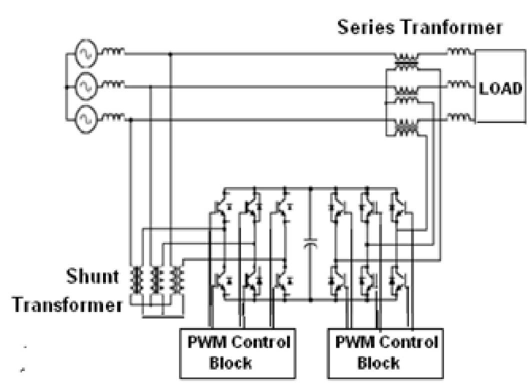
C. Combined Compensators

Combined compensators are combinations of series and shunt controllers. Combined compensators are: Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC).

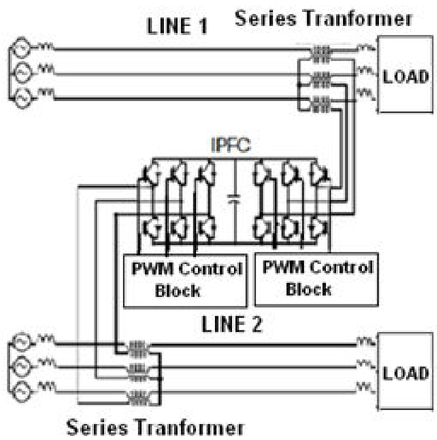
a) ***Unified Power Flow Controller (UPFC):*** A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent active and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the active and reactive power flow in the line. The UPFC may also provide [16-20] independently controllable shunt reactive compensation .The UPFC was developed for the real-time control and dynamic compensation of AC transmission systems. It is able to control all the parameters affecting power flow in the transmission line. Alternatively, it can independently control both the active and reactive power flow in line.

b) Interline Power flow Controller (IPFC): The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of active power between the ac terminals of the SSSC's and are controlled to provide independent reactive compensation for the adjustment of active power flow in each line and maintain the desired distribution for reactive power flow among the lines. The IPFC structure may also include a STATCOM, coupled to the IPFC's common dc link, to provide shunt reactive compensation and supply or absorbs the overall active power deficit of the combined SSSC's. [21-23] The IPFC addresses the problem of compensating a number of transmission lines at given substation .Series capacitive compensators are used to increase the transmittable active power over a given line but they are unable to control the reactive power flow in, and thus the proper load balancing of the line . With IPEC active power can be transferred between different lines. Therefore, it is possible to:

- Equalize both active and reactive power flow between the lines,
- Reduce the burden of overloaded lines by active power transfer,



(a) UPFC Controller



(b) IPFC Controller

Fig. 7 Basic Structure of Combined Controllers

- Compensate against resistive line voltage drops and the corresponding reactive power demand,
- And increase the effectiveness of the overall compensating system for dynamic disturbances.

D. Facts Controllers with Energy Storage:

A superconducting magnetic energy storage (SMES) system is a device for storing and instantaneously discharging large quantities of power. It stores energy in the magnetic field created by the flow of DC current in a coil of superconducting material that has been cryogenically cooled. These systems have been in use for several years to improve industrial power quality and to provide a premium-quality service for individual customers vulnerable to of times without any degradation of the magnet. Recharge time can be accelerated to meet specific requirements, depending on system capacity. It is claimed that SMES is 97-98% efficient and it is much better at providing reactive power on demand. Energy storage is becoming increasingly important to provide backup power for transmission outages, maintain power quality and for peak shaving. An energy storage device is interfaced to the DC bus of a Voltage Source Converter, possibly through a secondary power conversion stage. The voltage sourced converter thus acts like a STATCOM attached to an energy source.

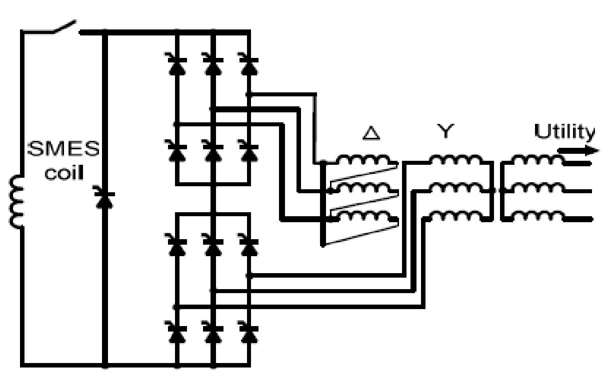


Fig. 8 Basic Structure of SMES Controller

III. COSTS

As compared to conventional devices, Flexible AC Transmission System controllers [24-25] are very expensive. The approximate cost per KVar output of various conventional devices and Flexible AC Transmission System controllers are shown in Table I. However, the cost per kVar decreases for higher capacity of Flexible AC Transmission System controllers. The total cost also depends on the size of fixed and controlled portion of the Flexible AC Transmission System controllers. The Flexible AC Transmission System equipment cost represent only half of the total FACTS project cost. Other costs like construction works, installation, commissioning, engineering and project management constitute the other half of the FACTS project cost.

Table I: Cost of Conventional and Flexible AC Transmission Controllers

FACTS Controllers	Cost (IN RS.)
Shunt Capacitor	400/ kVar
Series Capacitor	1000/ kVar
SVC	2000/ kVar controlled portions
TCSC	2000/ kVar controlled portions
STATCOM	2500/ kVar
UPFC Series Portions	2500/ kVar through power
UPFC Shunt Portions	2500/ kVar controlled

IV. POTENTIAL RESEARCH AREAS IN FLEXIBLE AC TRANSMISSION TECHNOLOGY

Transmission and distribution network configurations, load characteristics, system operating conditions and meeting contingency situations, stability under large system disturbance dictate the applications of different types of Flexible AC Transmission System devices. Owing to frequently changing power transfer patterns, the ongoing restructuring of power systems will pose new stability problems. FACTS Controllers will also be required to ensure global stability objectives. Power systems are seeing a wider application of distributed measurement technology using global positioning system (GPS) and phasor measurement units (PMUs) for increase in overall system stability [25] in near future.

V. CONCLUSIONS

Although Flexible AC Transmission System technology appeared just a short time ago, it presents a wonderful perspective before our eyes. This paper presented a comprehensive literature survey on Flexible AC Transmission System technology and state-of-art Flexible AC Transmission System controlling devices .The state-of-art Flexible AC Transmission System controllers and their relative strengths and performance over traditional reactive power compensating devices are presented. Further research areas in the advanced electronics based Flexible AC Transmission System technology are indicated.

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