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Analysis of Facts Controllers in Transmission Lines

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Abstract:-This paper main aim to lightning in FACTS controller devices which can be effectively used for power flow control, load sharing among parallel corridors, voltage regulation, enhancement of transient stability and mitigation of system oscillations in Transmission line.
Keywords:-FACTS Controller, Power Transmission Network, Series Controller, Shunt Controller, Combined Series Shunt Controllers, Combined Series Shunt Controllers.

I. INTRODUCTION

For reduction of cost and improved reliability, most of the world's electric power systems continue to be interconnected. Interconnections take advantage of diversity of loads, availability of sources and fuel price for supplying power to loads at minimum cost and pollution with a required reliability. In a deregulated electric service environment, an effective electric grid is essential to the competitive environment of reliable electric service.

Now-a-days, greater demands have been placed on the transmission network, and these demands will continue to rise because of increasing number of nonutility generators and greater competition among utilities themselves. It is not easy to acquire new rights of way. Compensation in power system is, therefore, essential to alleviate some of these problems. Series/shunt compensation has been in use for past many years to achieve this objective.

The rapid development of power electronics technology provides exciting opportunities to develop new power system equipment for better utilization of existing systems. Since 1990, a number of control devices under the term FACTS technology have been proposed and implemented. FACTS device can be effectively used for power flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations. By giving additional flexibility, FACTS controllers can enable a line to carry power closer to its thermal rating. Mechanical switching has to be supplemented by rapid response power electronics. It may be noted that FACTS is an enabling technology, and not a one-on-one substitute for mechanical switches.

FACTS employ high speed thyristors for switching in or out transmission line components such as capacitors, reactors or phase shifting transformer for some desirable performance of the systems. The FACTS technology is not a single high power controller, but rather a collection of controllers, which can be applied individually or in coordination with others to control one or more of the system parameters.

In brief, FACTS are defined as

"Alternating current transmission systems incorporating power-electronic based and other static controllers to enhance controllability and increase power transfer capability."

II. LITERATURE REVIEW

A literature review was conducted to analysis the Role and Importance of FACTS Controllers in transmission line. N.G. Hingorani and L. Gyugyi [1] and R. K. Verma [2] has tried to understanding the concept of FACTS Devices and Controllers. These devices are use for the maintaining the power flow control, load sharing among parallel corridors, voltage regulation, enhancement of transient stability and mitigation of system oscillations in Transmission line.

III. TYPES OF FACTS CONTROLLERS

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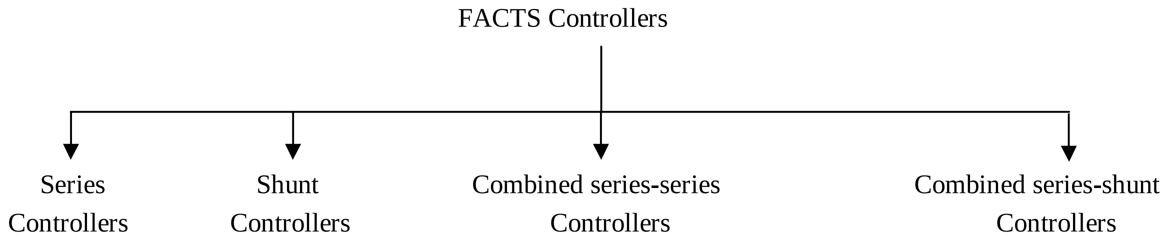

A. Basic types of FACTS Controllers

1) Series Controller; 2) Shunt Controller; 3) Unified series-series Controller; 4) Coordinated series and shunt Controller; 5) Unified series-shunt Controller; 6) Unified Controller for multiple lines; 7) Series Controller with storage; 8) Shunt Controller with storage; 9) Unified series-shunt Controller with storage.

IV. SERIES CONTROLLERS

The Series Controller could be variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series controllers inject voltage in series with the line and the purpose of series compensation is to cancel part of the series inductive reactance of the line using series capacitors. This helps in (i) increase of maximum power transfer (ii) reduction in power angle for a given amount of power transfer (iii) increased loading. From practical point of view, it is desirable to exceed series compensation beyond 80%. If the line is 100% compensated, it will behave as a purely resistive element and would cause series resonance even at fundamental frequency. The location of series capacitor is decided by economical factors and severity of fault currents. Series capacitor reduces line reactance thereby level of fault currents.

A capacitor in series with a line gives control over the effective reactance between line ends. This effective reactance is given by

$$Xl' = Xl - Xc$$

where

Xl = line reactance

Xc = capacitor reactance

It is easy to see that capacitor reduces the effective line reactance. It resulted in improvement in performance of the system as below:

Voltage drop in the line reduces (gets compensated) i.e. minimization of end voltage variations.

Prevents voltage collapse.

Steady state power transfer increases; it is inversely proportional to Xl'.

As a result of 2., transient stability limit increases.

The benefits of the series capacitor compensator are associated with a problem. The capacitive reactance Xc forms a series resonant circuit with the total series reactance :

$$X = Xl + Xgen + Xtrans$$

The natural frequency of oscillation of this circuit is given by

$$fc = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{\frac{X}{2\pi f}\frac{2\pi fC}{2\pi f}}}$$

$$=f\sqrt{\frac{Xc}{X}}$$

Where

f = system frequency

$\frac{Xc}{X}$ = degree of compensation

= 25 to 75% (recommended)

For this degree of compensation, fc < f which is sub harmonic oscillation.Even though series compensation has often been found to be cost effective compared to shunt compensation, but sustained oscillations below the fundamental system frequency can cause the phenomenon, referred to as subsynchronous resonance (SSR).

Series controllers can be classified as

Thyristor based controller

Thyristor controlled series compensator (TCSC)

Voltage source converter based controllers

Static synchronous series compensator (SSSC)

A. *Thyristor Controlled Series Compensator (TCSC)*

A TCSC is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. It is a capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor controlled reactor in order to provide smoothly variable series capacitive reactance. The principle of variable series compensation from the system viewpoint is to simply increase the fundamental frequency voltage across a fixed capacitor in a series compensated line through appropriate variation of the firing angle α. This enhanced voltage changes the effective value of the series capacitive reactance.

TCSC is very helpful in suppression of sub synchronous oscillations. At sub synchronous frequencies the TCSC presents an inherently resistive-inductive reactance which effectively damps the subsynchronous oscillations. It also can potentially limit short circuit currents. During events of high short circuit currents the TCSC can switch from controllable capacitance to bypassed mode (in which the TCSC presents itself as a net inductive reactance), thereby restricting the short circuit current.

The basic conceptual TCSC module is comprised of a series capacitor C in parallel with a thyristor controlled reactor LS as shown in fig. 1(a).

However, a practical TCSC module will also include protective equipment normally installed with series capacitors, such as, metal oxide varistor (MOV), circuit breaker CB, and an ultra high speed contact (UHSC) across the valve as depicted in Fig. 1(b).

The behaviour of TCSC is quite similar to that of the parallel inductor-capacitor combination. The difference, however, is that the LC combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit whereas in TCSC the voltage and current in the fixed capacitor and thyristor controlled reactor are not sinusoidal owing to thyristor switching.

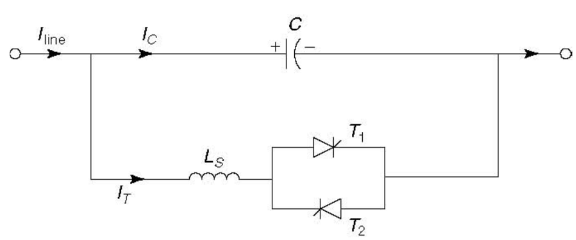

Fig. 1(a) Thyristor controlled reactor LS

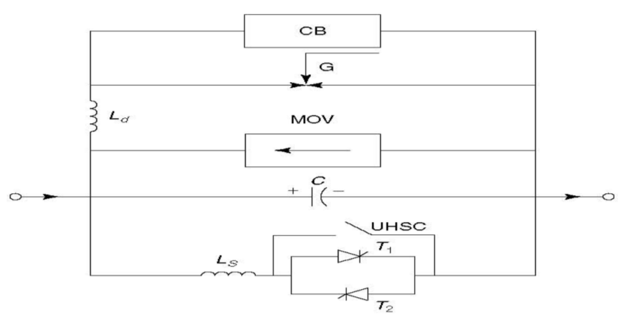

Fig. 1(b) ultra high speed contact (UHSC) across the valve

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The TCSC provides both continuously controllable capacitive and inductive operation but does not provide a smooth transition between the capacitive and inductive mode due to a resonance situation. This is avoided by splitting a single TCSC into multiple segments/modules and operating them independently in inductive and capacitive modes.

B. Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator, commonly known as SSSC or S3C is a series connected synchronous voltage source which can vary the effective impedance of a transmission line by injecting a voltage with an appropriate phase angle in relation to the line current. It has the capability of exchanging both real and reactive power with the transmission system. For instance, if the injected voltage is in phase with the line current then it exchanges real power. On the other hand if a voltage is injected in quadrature with the line current then reactive power is exchanged – either absorbed or generated. SSSC emerges as a potentially more beneficial Controller in comparison to a TCSC. This is because of its ability to not only modulate the line reactance but also the line resistance in consonance with the power swings thereby imparting an enhanced damping to the generators participating in the power oscillations.

The SSSC comprises a multi-pulse voltage source converter (VSC) with a dc energy storage controller as depicted in Fig. 2(a). The Controller is connected in series with the transmission line. The operating modes of SSSC are graphically illustrated in Fig. 2(b). A series capacitor compensates the transmission line inductance by presenting a lagging quadrature voltage with respect to the transmission line current and which acts in opposition to the leading quadrature voltage appearing across the transmission line inductance. This has a net effect of reducing the line inductance. Similar is the operation of an SSSC that also injects a quadrature voltage VC in proportion to the line current but lagging in phase.

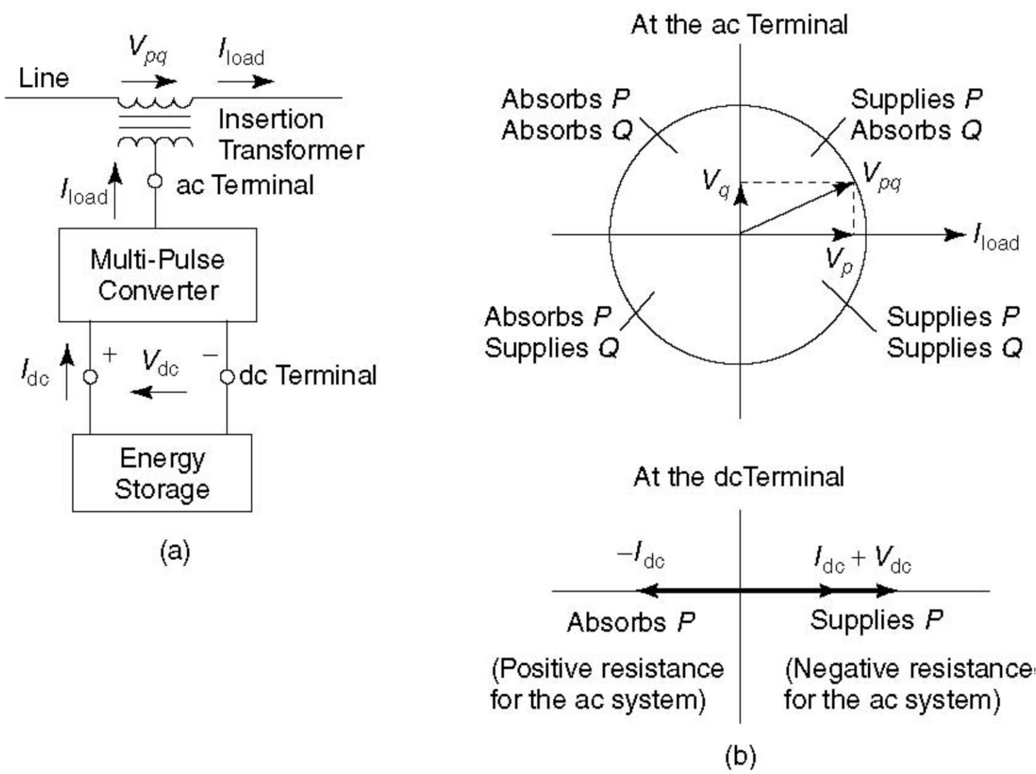

Fig. 2(a) & 2(b): Operational block diagram of a SSSC

V. SHUNT CONTROLLERS

As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Even a variable shunt impedance connected

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to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Shunt compensators are connected in shunt at various system nodes (major substations) and sometimes at mid-point of lines. These serve the purposes of voltage control and load stabilization. As a result of installation of shunt compensators in the system, the nearby generators operate at near unity pf and voltage emergencies mostly do not arise.

Shunt controllers can be classified as

- Thyristor based controller
  - Static Var Compensator (SVC)
- Voltage source converter based controllers
  - Static synchronous compensator (STATCOM)

A. *Static Var Compensator (SVC)*

"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)".

This is a general term for a thyristor-controlled or hyristor-switched reactor, and/or thyristor-switched capacitor or combination Fig.3. SVC is based on thyristors without the gate turn-off capability. It includes separate equipment for leading and lagging vars; the thyristor-controlled or thyristor-switched reactor for absorbing reactive power and thyristor-

Switched capacitor for supplying the reactive power. SVC is considered by some as a lower cost alternative to STATCOM, although this may not be the case if the comparison is made based on the required performance and not just the MVA size.

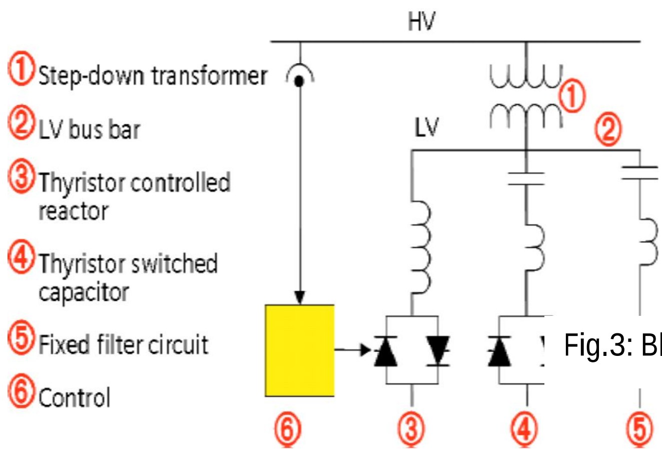

Fig.3: Block diagram of SVC

Fig 3. Static var generator

1) *Thyristor Controlled Reactor (TCR):* "A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve". TCR is a subset of SVC in which conduction time and hence, current in a shunt reactor is controlled by a thyristor-based ac switch with firing angle control.
2) *Thyristor Switched Reactor (TSR):* "A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve". TSR is another subset of SVC. TSR is made up of several shunt connected inductors which are switched in and out by thyristor switches without any firing angle controls in order to achieve the required step changes in the reactive power consumed from the system. Use of thyristor switches without firing angle control results in lower cost and losses, but without a continuous control.
3) *Thyristor Switched Capacitor (TSC):* "A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve". TSC is also a subset of SVC in which thyristor based ac switches are used to switch in and out (without firing angle control) shunt capacitors units, in order to achieve the required step change in the reactive power supplied to the system. Unlike shunt reactors, shunt capacitors cannot be switched

continuously with variable firing angle control.

The steady state and dynamic characteristics of an SVC describe the variation of SVC bus voltage with SVC current figure 4 illustrates the terminal voltage - SVC current characteristic. The dynamic V-I characteristics of the SVC is described by its linear range of control over which SVC terminal voltage varies linearly with SVC current as the latter is varied over its entire capacitive to inductive range. When the SVC traverses outside the linear controllable range on the inductive side the SVC enters the overload zone where it behaves like a fixed inductor. A small slope (2-3%) is incorporated in the V-I characteristic for improved SVC operation.

In order to prevent the thyristor valves from being subjected to excessive thermal stresses the maximum inductive current in the overload range is constrained to a constant value by an additional control action. The steady state V-I characteristic of an SVC is very similar to the dynamic V-I characteristic except for a dead band in voltage. In the absence of this deadband, in steady-state, the SVC will have a tendency to drift towards its reactive power limits to provide voltage regulation, thus undesirably limiting the dynamic range of SVC available for system performance improvement.

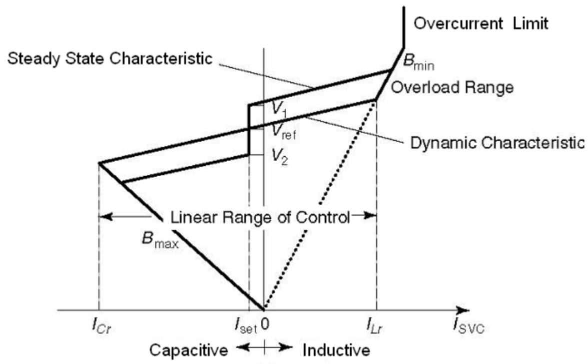

Fig.4 thyristor switched capacitor (tsc)

B. Static Synchronous Compensator (STATCOM)

A 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 single line STATCOM power circuit is shown in Figure 5(a). A voltage source converter is connected to utility bus through magnetic coupling. As shown in Figure 5(b), a STATCOM can be seen as an adjustable voltage source behind a reactance. This implies that capacitor banks and shunt reactors are not needed for generation and absorption of reactive power, giving a compact design, a small footprint, as well as low noise and low magnetic impact.

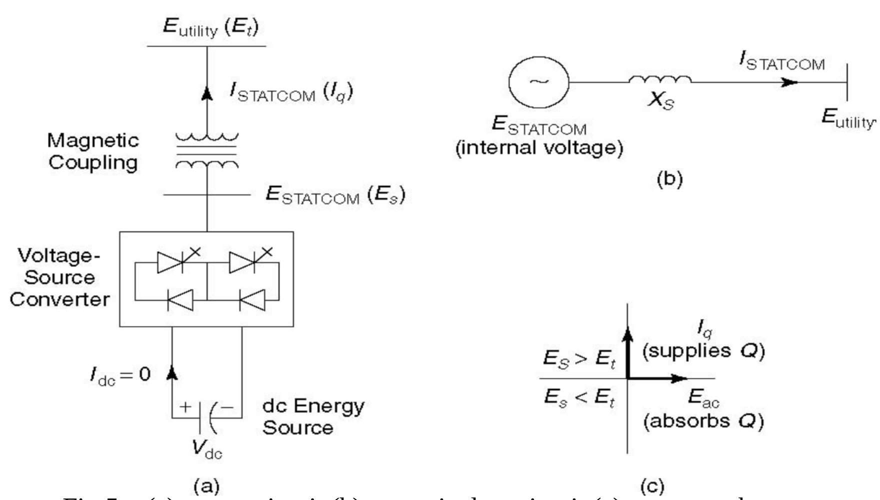

Fig 5: (a) power circuit (b) an equivalent circuit (c) power exchange

Reactive power exchange between the converter and the ac system can be controlled by varying the amplitude of the three-phase output voltage, Es, of the converter as illustrated in Figure 5(c). If the amplitude of the output voltage is increased above that of the utility bus voltage, Et, then a current flows, through the reactance, from the converter to the ac system, and the converter generates capacitive reactive power for the ac system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter, and the converter absorbs inductive reactive power from the ac system. If the output voltage equals the ac system voltage, the reactive power exchange becomes zero, and the STATCOM is said to be in a floating state.

Adjusting the phase shift between the converter output voltage and the ac system voltage can similarly control real power exchange between the converter and the ac system. That is, the converter can supply real power to the ac system from its dc energy storage if the converter output voltage is made to lead the ac system voltage. On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags the ac system voltage.

A typical V-I characteristic of a STATCOM is depicted in Figure 6. As can be seen, the STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of the ac system voltage. The STATCOM can provide full capacitive reactive power at any system voltage, as low as even 0.15 pu. This characteristic of a STATCOM reveals another strength of this technology: it is capable of yielding full output of capacitive generation almost independently of the system voltage (constant current output at lower voltages). This is particularly useful in situations where the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.

VI. COMBINED SERIES-SERIES CONTROLLERS

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "unified" here means that the dc terminals of all Controller converters are all connected together for real power transfer.

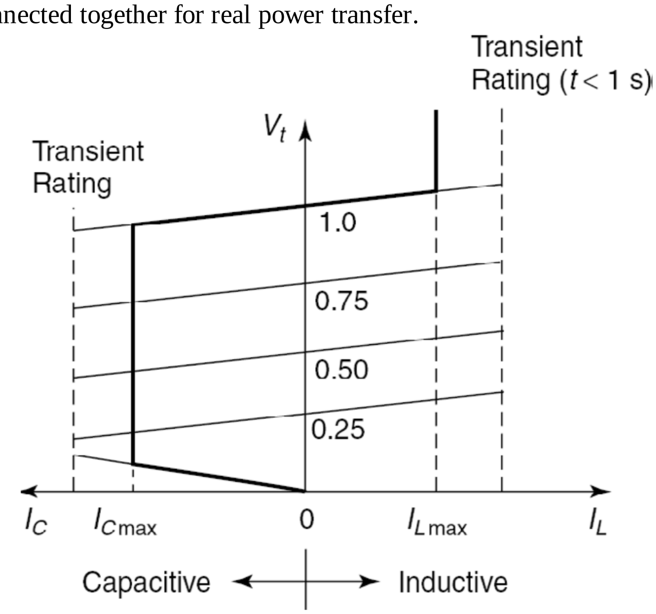

Fig.6: V-I characteristic of a STATCOM

VII. INTERLINE POWER FLOW CONTROLLER (IPFC)

The IPFC is a recently introduced Controller and thus has no IEEE definition yet. A possible definition is “The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment

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of real power flow in each line and maintain the desired distribution of reactive power flow among the lines. The IPFC structure may also include a STATCOM, coupled to the IFFC's common dc link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSCs".

VIII. COMBINED SERIES-SHUNT CONTROLLER

This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner, or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.

A. Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller (UPFC) is the most versatile FACTS Controller developed so far with all-encompassing capabilities of voltage regulation, series compensation and phase shifting. It can independently control both the real and reactive power flows in a transmission line at an extremely rapid rate.

The UPFC is configured as shown in Fig.7. It comprises two voltage source converters (VSCs) coupled through a common dc terminal. One VSC - Converter 1 is connected in shunt with the line through a coupling transformer and the other VSC - Converter 2 is inserted in series with the transmission line through an interface transformer. The dc voltage for both converters is provided by a common capacitor bank. The series converter is controlled to inject a voltage Vpq in series with the line, which can be varied between 0 and Vpqmax. Moreover, the phase angle of the phasor Vpq can be independently varied between 0o and 360o. In this process the series converter exchanges both real and reactive power with the transmission line. While the reactive power is internally generated/absorbed by the series converter, the real power generation/absorption is made feasible by the dc energy storage device i.e. the capacitor. The shunt connected Converter 1 is mainly used to supply the real power demand of Converter 2, which it derives from the transmission line itself. The shunt converter maintains the voltage of the dc bus constant. Thus the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers. In addition, the shunt converter functions like a STATCOM and independently regulate the terminal voltage of the interconnected bus by generating/absorbing requisite amount of reactive power.

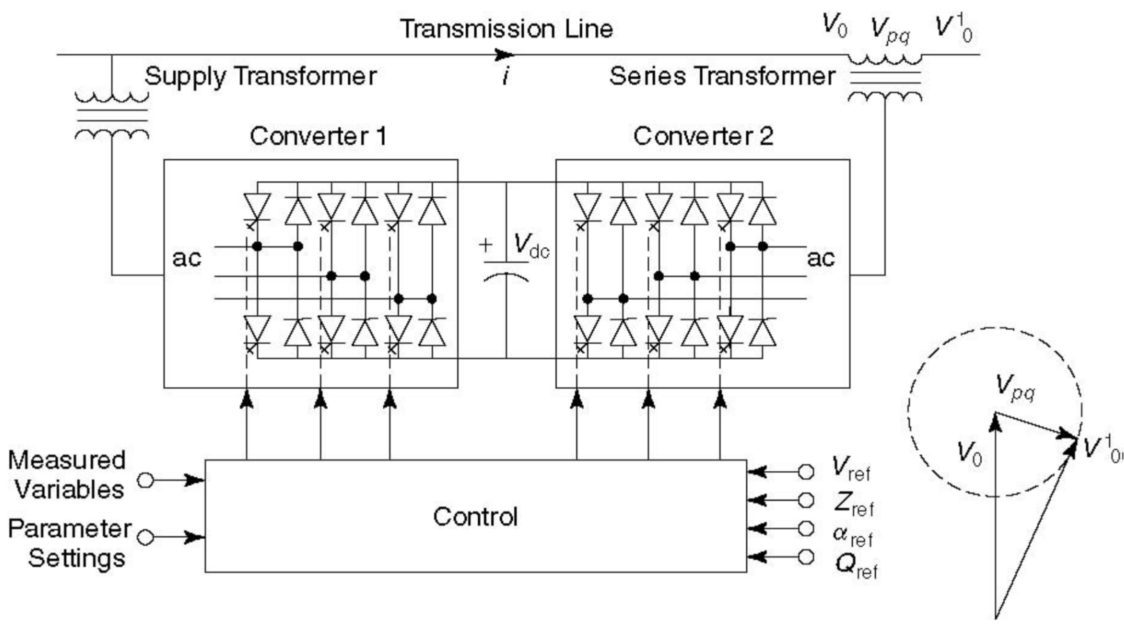

Fig.7: Implementation of UPFC by two back-to-back Voltage Sourced Converters

IX. CONCLUSION

All existing FACTS controllers functioning according to the proposed scheme, which can be effectively used for power flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations in Transmission line and the technology behind phase controlled thyristor based FACTS Controller has been operation since few decades and is therefore considered mature. More utilities are likely to continue adopting this technology in future. However, the second generation of FACTS Controllers such as STATCOM, SSSC and UPFC utilizing voltage source converter (VSC) configurations based on GTOs and IGBTs offer greater advantages and are being increasingly installed globally. Recent advances in silicon power switching devices resulting in significant increases in their power ratings will contribute even further to the growth of FACTS Technology.

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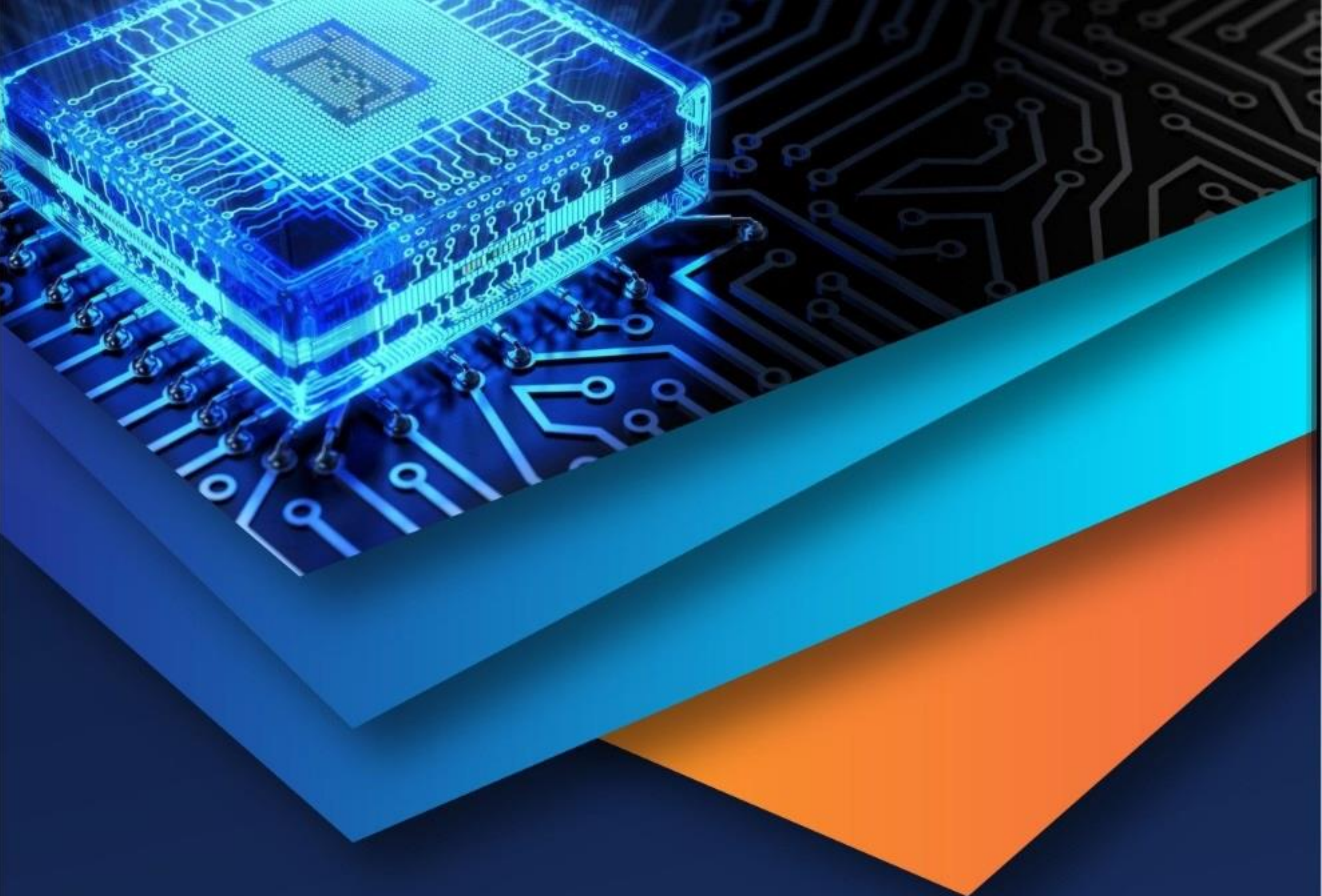

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