ENHANCEMENT OF SERIES COMPENSATION FOR LONG TRANSMISSION LINE BY USING UNIFIED POWER FLOW CONTROLLERS

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ABSTRACT

This paper deals with the optimal location and parameters of Unified Power Flow Controllers (UPFCs) in electrical power systems. The UPFC is one of the most promising FACTS devices in terms of its ability to control power system quantities. Shunt FACTS devices are used for controlling transmission voltage, power flow, reducing reactive losses, and damping of power system oscillations for high power transfer levels. In this paper the optimal location of a shunt FACT device is investigated for an actual line model of a transmission line having series compensation at the centre. As one of the most promising FACTS devices in terms of its ability to control power system quantities, UPFC Effect of change in degree of series compensation on the optimal placement of the shunt FACTS device to get the highest possible benefit is studied. The results obtained shown that optimal placement of the shunt FACTS device varies with the change in the level of series compensation.

Key Words: ***Optimal placement, Shunt FACTS, Series compensation, Unified power flow controller (UPFC), long transmission line etc***

1. INTRODUCTION

The flexible AC transmission system (FACTS) has received much attention in the last 2 decades. It uses high current power electronic devices to control the voltage, power flow, stability, etc. of a transmission system. FACTS technologies can essentially be defined as highly engineered power-electronics-based systems, integrating the control and operation of advanced power semiconductor based converters (or valves) with software based information and control systems, which produce a compensated response to the transmission network that is interconnected via conventional switchgear and transformation equipment. FACTS devices can be connected to a transmission line in various ways, such as in series with the power system (series compensation), in shunt with the power system (shunt compensation), or both in series and shunt. For example, the static VAR compensator (SVC) and static synchronous compensator (STATCOM) are connected in shunt; static synchronous series compensator (SSSC) and thyristor controlled series capacitor (TCSC) are connected in series; thyristor controlled phase shifting transformer (TCPST) and unified power flow controller (UPFC) are connected in a series and shunt combination. In series compensation, the FACTS is connected in series with the power system. It works as a controllable voltage source. Series inductance occurs in long transmission lines, and when a large current flow causes a large voltage drop. To compensate, series capacitors are connected. In shunt compensation, power system is connected in shunt with the FACTS.

It works as a controllable current source. The term and definition of various FACTS devices are described in references [1]-[5]. The pressure associated with economical and environmental constraints has forced the power utilities to meet the future demand by fully utilizing the existing resources of transmission facilities without building new lines. FACTS devices are very effective and capable of increasing the power transfer capability of a line, as thermal limits permit, while maintaining the same degree of stability [3]-[9]. Numerous recent applications of FACTS have proven to be cost-effective, long-term solutions. With the improvements in current and voltage handling capabilities of the power electronic devices that have allowed for the development of Flexible AC Transmission System (FACTS), The possibility has arisen in using different types of controllers for efficient shunt and series compensation. Applying FACTS on a broad-scale basis for both local and. Shunt FACTS devices are used for controlling transmission voltage, power flow, reducing reactive losses, and damping of power system oscillations for high power transfer levels [5]-[8]-[9].With the wide spread and active consideration of the installation of FACTS controllers for better controllability.

1.1 General:

Modern power systems are designed to operate efficiently to supply power on demand to various load centres with high reliability. The generating stations are often located at distant locations for economic, environmental and safety reasons. For example, it may be cheaper to locate a thermal power station at pithead instead of transporting coal to load centres. Hydropower is generally available in remote areas. A nuclear plant may be located at a place away from urban areas.

Thus, a grid of transmission lines operating at high or extra high voltages is required to transmit power from the generating stations to the load centres.

In addition to transmission lines that carry power from the sources to loads, modern power systems are also highly interconnected for economic reasons. The interconnected systems benefit by

(a) Exploiting load diversity (b) Sharing of generation reserves and

(c) Economy gained from the use of large efficient units without sacrificing reliability.

However, there is also a downside to ac system interconnection { the security can be adversely affected as the disturbances initiated in a particular area can spread and propagate over the entire system resulting in major blackouts caused by cascading outages.

1.2 Basics of Power Transmission Networks:

A large majority of power transmission lines are AC lines operating at different voltages (10 kV to 800 kV). The distribution networks generally operate below 100 kV while the bulk power is transmitted at higher voltages. The lines operating at different voltages are connected through transformers which operate at high efficiency. Traditionally, AC lines have no provision for the control of power flow. The mechanically operated circuit breakers (CB) are meant for protection against faults (caused by flashovers due to overvoltages on the lines or reduced clearances to ground). A CB is rated for a limited number of open and close operations at a time and cannot be used for power flow control. (Unlike a high power electronic switch such as thyristor, GTO, IGBT, IGCT, etc.).

Fortunately, ac lines have inherent power flow control as the power flow is determined by the power at the sending end or receiving end. For example, consider a transmission line connecting a generating station to a load centre in Fig.1.1. Assuming the line to be lossless and ignoring the line charging, the power flow (P) is given by

$$P = \frac{V_1 V_2}{X} \sin(\theta_1 - \theta_2)$$

Where X is the series line reactance. Assuming V_1 and V_2 to be held constants (through voltage regulators at the two ends),

The power injected by the power station determines the flow of power in the line. The difference in the bus angles is automatically adjusted to enable $P = P_G$ (Note that usually there could be more than one line transmitting power from a generating station to a load centre). If one or more lines trip, the output of the power station may have to be reduced by tripping generators, so as to avoid overloading the remaining lines in operation.

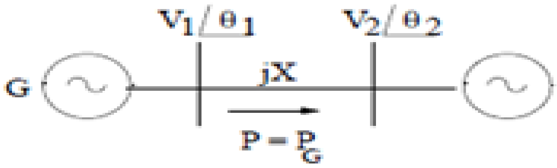


Fig 1.1 A line transmitting power form a generating station

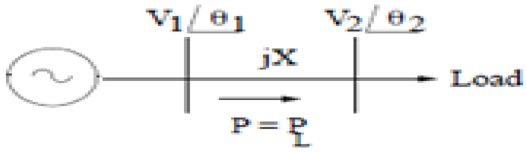


Fig 1.2 A line supplying power to load

Fig. 1.2 shows another situation where a line supplies power to a load located at bus (2). Here also the eq. applies but the power flow in the line is determined by the load supplied. The essential difference between the two situations is that in Fig. 1.1 the load centre is modelled as an infinite bus which can absorb (theoretically) any amount of power supplied to it from the generating station. This model of the load centre assumes that the generation available at the load centre is much higher than the power supplied from the remote power station (obviously, the total load supplied at the load centre is equal to the next generation available at that bus).

The reliability of the power supply at a load bus can be improved by arranging two (or more) sources of power as shown in Fig. 1.2.1 Here, P_1 is the output of G_1 while P_2 is the output of G_2 (Note that we are neglecting losses as before). However, the tripping of any one line will reduce the availability of power at the load bus. This problem can be overcome by providing a line to interconnect the two power stations. Note that this results in the creation of a mesh in the transmission network. This improves the system reliability, as tripping of any one line does not result in curtailment of the load. However, in steady state, P_1 can be higher or lower than P_{G1} (the output of G_1).The actual power flows in the 3 lines forming a mesh are determined by Kirchhoff's Voltage Law (KVL).

In general, the addition of an (interconnecting) line can result in increase of power flow in a line (while decreasing the power flow in some other line). This is an interesting feature of AC transmission lines and not usually well understood (in the context of restructuring). In general, it can be stated that in an uncontrolled AC transmission network with loops (to improve system reliability), the power flows in individual lines are determined by KVL and do not follow the requirements of the contracts (between energy producers and customers).

In other words, it is almost impossible to ensure that the power flow between two nodes follows a predetermined path. This is only feasible in radial networks (with no loops), but the reliability is adversely affected as even a single outage can result in load curtailment. Consider two power systems, each with a single power station meeting its own local load, interconnected by a tie line as shown in Fig. 1.2.1.In this case, the power flow in the tie line (P) in steady state is determined by the mismatch between the generation and load in the individual areas. Under dynamic conditions, this power flow is determined from the equivalent circuit shown in Fig. 1.2.2.If the capacity of the tie is small compared to the size (generation) of the two areas, the angles ±1 and ±2 are not affected much by the tie line power flow.

Thus, power flow in AC tie is generally uncontrolled and it becomes essential to trip the tie during a disturbance, either to protect the tie line or preserve system security. In comparison with a AC transmission line, the power flow in a HVDC line in controlled and regulated.

However, HVDC converter stations are expensive and HVDC option is used primarily for (a) long distance bulk power transmission (b) interconnection of asynchronous systems and (c) underwater (submarine) transmission. The application of HVDC transmission (using thyristor converters) is also constrained by the problem of commutation failures affecting operation of multiterminal or multi-feed HVDC systems. This implies that HVDC links are primarily used for point-to-point transmission of power and asynchronous interconnection (using Back to Back (BTB) links).

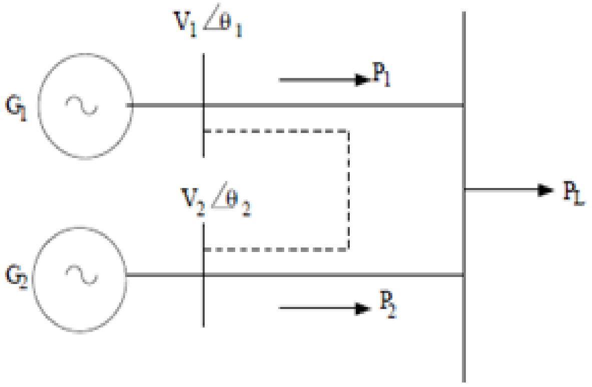
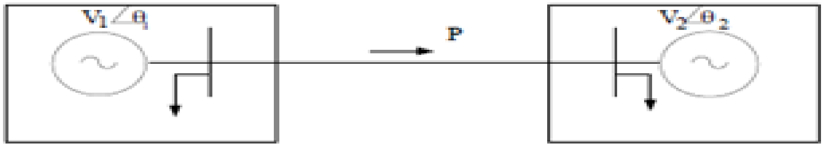
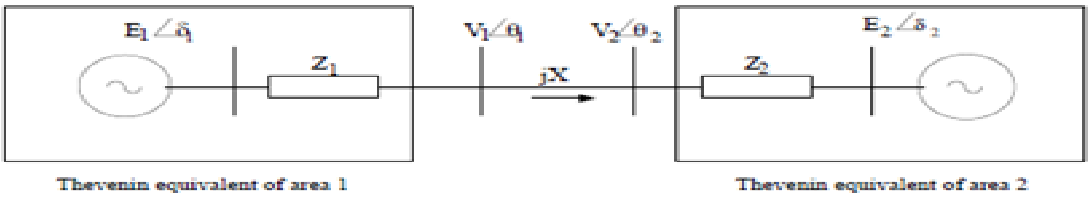


Fig 1.2.1 Two generating station supplying load



(a)Single line diagram



(b)Equivalent circuit

Fig 1.2.2 two areas connected by a tie line

1.3 Control of Power Flow in AC Transmission Line:

We may like to control the power flow in a AC transmission line to (a) enhance power transfer capacity and or (b) to change power flow under dynamic conditions (subjected to disturbances such as sudden increase in load, line trip or generator outage) to ensure system stability and security. The stability can be affected by growing low frequency, power oscillations (due to generator rotor swings), loss of synchronism and voltage collapse caused by major disturbances.

From eq. (1.1), we have the maximum power ($P_{\max}$) transmitted over a line as

$$P_{\max} = \frac{V_1 V_2}{X} \sin \delta_{\max} \tag{1.2}$$

Where δ_{max} (30^0– 40^0) is selected depending on the stability margins and the stiffness of the terminal buses to which the line is connected. For line lengths exceeding a limit, P_{max} is less than the thermal limit on the power transfer determined by the current carrying capacity of the conductors (Note this is also a function of the ambient temperature). As the line length increases, X increases in a linear fashion and P_{max} reduces as shown in Fig. 1.3

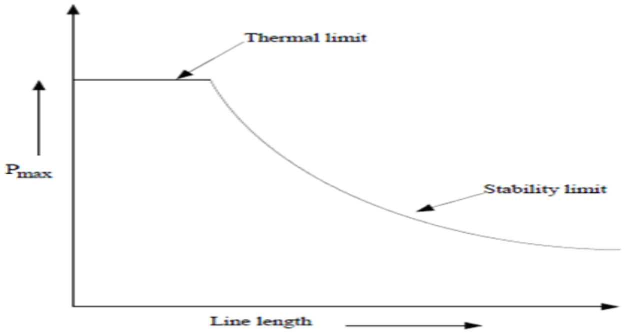


Fig 1.3 power Transfer Capacity as a function of line length

The series compensation using series connected capacitors increases P_{max} as the compensated value of the series reactance (Xc) is given by

$$X_c = X(1 - k_{se}) \qquad (1.3)$$

Where k_{se} is the degree of series compensation. The maximum value of k_{se} that can be used depends on several factors including the resistance of the conductors. Typically k_{se} does not exceed 0.7. Fixed series capacitors have been used since a long time for increasing power transfer in long lines. They are also most economical solutions for this purpose.

However, the control of series compensation using thyristor switches has been introduced only 10{15 years ago for fast power flow control. The use of Thyristor Controlled Reactors (TCR) in parallel with fixed capacitors for the control of X_c, also helps in overcoming a major problem of Sub synchronous Resonance (SSR) that causes instability of torsional modes when series compensated lines are used to transmit power from turbo generators in steam power stations. In tie lines of short lengths, the power flow can be controlled by introducing Phase Shifting Transformer (PST) which has a complex turn's ratio with magnitude of unity. The power flow in a lossless transmission line with an ideal PST (see Fig. 1.4) is given

$$P = \frac{V_1 V_2}{X} \sin(\theta \pm \phi) \qquad (1.4)$$

where $\theta = \theta_1 - \theta_2$.

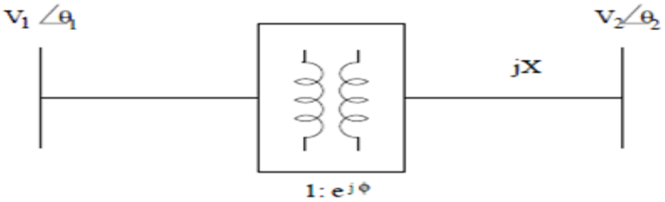


Fig 1.4 A Lossless line with an ideal PST

Again, manually controlled PST is not fast enough under dynamic conditions. Thyristor switches can ensure fast control over discrete (or continuous) values of §, depending on the configuration of PST used. P_{max} can also be increased by controlling (regulating) the receiving end voltage of the AC line. When a generator supplies a unity power factor load (see Fig. 1.2, the maximum power occurs when the load resistance is equal to the line reactance). It is to be noted that V2 varies with the load and can be expressed as

$$V_2 = V_1 \cos(\theta_1 - \theta_2) \qquad (1.5)$$

Substituting (1.5) in (1.1) gives

$$P = \frac{V_1^2 \sin[2(\theta_1 - \theta_2)]}{2X} \qquad (1.6)$$

By providing dynamic reactive power support at bus (2) as shown in Fig. (1.5), it is possible to regulate the bus voltage magnitude.

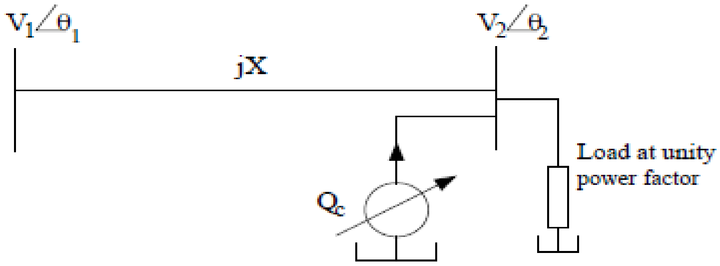


Figure 1.5: Transmission line compensated by controllable reactive power source.

At receiving end power (QC) that has to be injected is given by

$$Q_C = \frac{V_2^2 - V_1 V_2 \cos(\theta_1 - \theta_2)}{X} \qquad (1.7)$$

Comparing eq. (1.6) with (1.1), it can be seen that the maximum power transfer can be doubled just by providing dynamic reactive power support at the receiving end of the transmission line. This is in addition to the voltage support at the sending end. It is to be noted that while steady state voltage support can be provided by mechanically switched capacitors, the dynamic voltage support requires synchronous condenser or a power electronic controller such as Static Var Compensator (SVC) or Static synchronous Compensator (STATCOM).

2. Comparison between Series and Shunt Capacitor:

The maximum power flow in the line is given by substituting + in the expression for the power flow (P) is chosen from considerations of the steady state margin that will not result in the power flow exceeding limits during a contingency. For the same amount of maximum power transfer, we obtain the following relation

$$\frac{B_c}{2} Z_n \tan\frac{\theta}{2} = \frac{X_c}{2 Z_n \tan\frac{\theta}{2}}$$

While transferring maximum power, the reactive power (Qse) supplied by the series capacitor (for a symmetric line with VS = VR = V) is given by

$$Q_{se} = I_m^2 X_c = \frac{V^2 \sin^2 \frac{\delta_{\max}}{2} X_c}{Z_n^2 \sin^2 \frac{\theta}{2} (1 - k_{se})^2}$$

The reactive power (Qsh) supplied by the shunt capacitor (Bc) at P = Pmax is obtained as

$$Q_{sh} = V_m^2 B_c = \frac{V^2 \cos^2 \frac{\delta_{\max}}{2} B_c}{\cos^2 \frac{\theta}{2} (1 - k_{sh})^2}$$

$$k_{sh} = \frac{B_c Z_n}{2} \tan\frac{\theta}{2}$$

The above relation shows that the series capacitor is much more effective than the shunt capacitor in increasing power transfer.

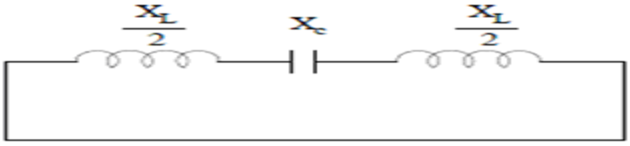


Fig 2.1 series capacitor

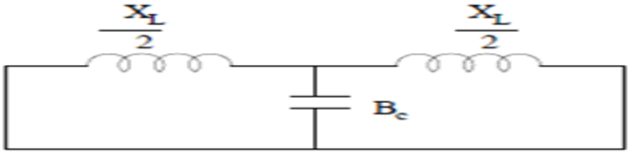


Fig 2.2 Shunt capacitor

Another factor in the comparison of the series and shunt (capacitor) compensation is the electrical resonance frequency. The comparison can be made from the Fig.3.1&3.2

The electrical resonance frequency (f seer) for the series capacitor compensation

$$f_{er}^{se} = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} = f_0\sqrt{\frac{X_c}{X_L}} = f_0\sqrt{(1-k_{se})}$$

The resonance frequency for the shunt capacitor compensation is obtained as

$$f_{er}^{sh} = f_0\sqrt{\frac{4}{B_c X_L}} = f_0\sqrt{\frac{1}{(1-k_{sh})}}$$

Where f0 is the operating system frequency (50 or 60 Hz).Note that in deriving these expression, the equation, XL2 = Zn tan µ 2 is used.

It is shown in reference [3] that oscillations of the generator rotor corresponding to a sub synchronous frequency torsional mode (of frequency, fm) causes amplitude modulation of the generator voltage. This causes two side bands of frequency (f0 - fm) and (f0 + fm) of the injected voltage, which result in a sub synchronous frequency and a super synchronous frequency current components °owing in the generator armature. While the sub synchronous frequency current component results in a negative damping torque, the super synchronous frequency current results in a positive damping torque. The electrical resonance at frequency, f0 - fm, increases the negative damping torque while resonance at f0+fm, results in increase in the positive damping torque.

This implies that there is no danger of Sub synchronous Resonance (SSR) with shunt capacitor, while it exists with the series capacitor. On the other hand, the rating of the shunt capacitor required is high unless the lines are substantially long resulting in large operating values of ±max. The cost of a series capacitor is higher (typically by a factor of 2) as it has to be designed to withstand overvoltages during fault transients.

2.1 Static VAR Compensator:

It is a variable impedance device where the current through a reactor is controlled using back to back connected thyristor valves. The application of thyristor valve technology to SVC is an overshoot of the developments in HVDC technology. The major difference is that thyristor valves used in SVC are rated for lower voltages as the SVC is connected to an EHV line through a step down transformer or connected to the tertiary winding of a power transformer. The application of SVC was initially for load compensation of fast changing loads such as steel mills and arc furnaces.

Here the objective is to provide dynamic power factor improvement and also balance the currents on the source side whenever required. The application for transmission line compensators commenced in the late seventies. Here the objectives are:

1. Increase power transfer in long lines 2. Improve stability with fast acting voltage regulation
3. Damp low frequency oscillations due to swing (rotor) modes 4. Damp sub synchronous frequency oscillations due to torsional modes 5. Control dynamic overvoltages

A SVC has no inertia compared to synchronous condensers and can be extremely fast in response (2-3 cycles). This enables the fast control of Reactive power in the control range.

2.1.1 Analysis of SVC:

The location of SVC is important in determining its effectiveness. Ideally, it should be located at the electrical centre of the system or midpoint of a transmission line. For example, consider a symmetric lossless transmission line with SVC connected at the midpoint (see Fig. 3.3). Without SVC, the voltage at the midpoint is given by,

$$V_{mo} = \frac{V\cos\delta/2}{\cos\theta/2}$$

Where µ = 1 is the electrical length of the line, l is the length of the line and is the phase constant given by

$$\beta = \omega\sqrt{lc} = 2\pi f\sqrt{lc}$$

Where l and c are positive sequence inductance and capacitance of the line per unit length, f is the operating frequency.

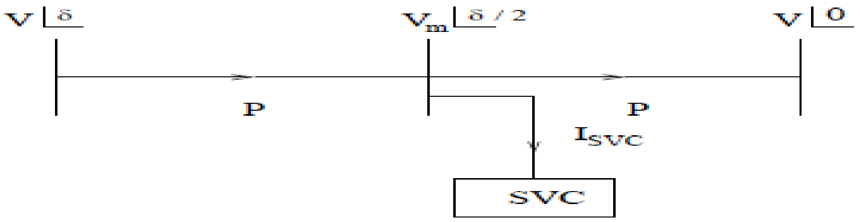


Fig 2.3 Analysis of SVC

It can be shown that the voltage variation in the line (due to variation in ±) is maximum at the midpoint. SVC helps to limit the variation by suitable control. The steady state control characteristics of SVC is shown in Fig. 3.4 where ADB is the control range. OA represents the characteristic where the SVC hits the capacitor limit, BC represents the SVC at its inductor limit. Note that SVC current is considered positive when SVC susceptance is inductive. Thus

$$I_{SVC} = -B_{SVC}V_{SVC}$$

The slope of OA is BC (susceptance of the capacitor) and the slope of OBC is BL (susceptance of the reactor). A positive slope (in the range of 1-5%) is given in the control range to (a) enable parallel operation of more than one SVC connected at the same or neighbouring buses and (b) prevent SVC hitting the limits frequently.

2.3 TRANSMISSION LINE MODEL:

In this study, it is considered that the transmission line parameters are uniformly distributed and the line can be modelled by a 2-port, 4-terminal networks as shown in Figure 3.16. This figure represents the actual line model. The relationship between sending end (SE) and receiving end (RE) quantities of the line can be written as:

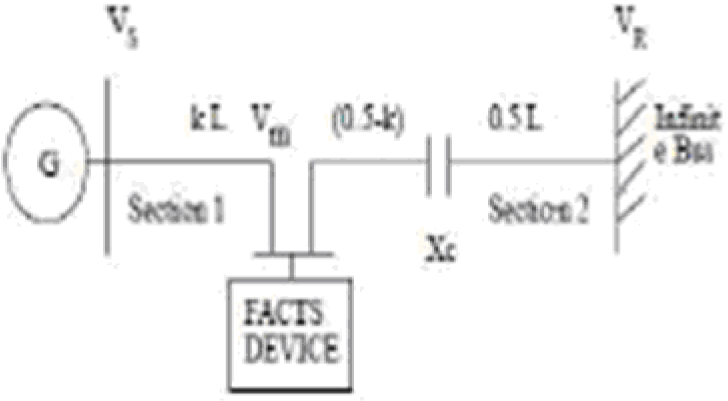


Fig 2.4 2-port,4-terminal model of a transmission line

2.4 SERIES COMPENSATED TRANSMISSION LINE WITH SHUNT FACTS DEVICES

Consider that the line is transferring power from a large generating station to an infinite bus and equipped with series capacitor at centre and a shunt FACT device at point ‘m’ as shown in Figure 2. Parameter k is used to show the fraction of the line length at which the FACTS device is placed. The shunt FACTS device may be a SVC or STATCOM and is usually connected to the line through a step-down transformer as shown in Figures 3.19 and 3.20. The transmission line is divided into 2 sections (1 & 2), and section 2 is further divided in subsections of length [(0.5-k) & half-line length]. Each section is represented by a separate 2-port, 4-terminal network (similar to Figure 2) with its own ABCD constants considering the actual line model

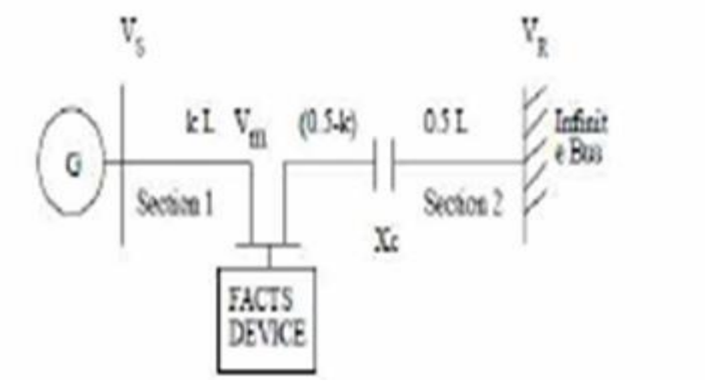


Fig 2.5 series compensated transmission line with a shunt Fact device

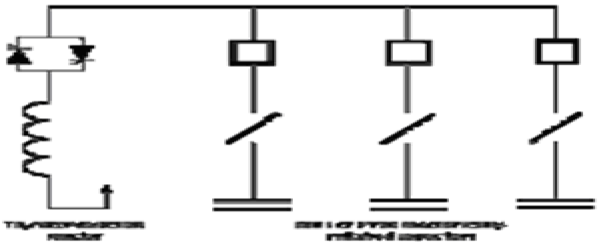


Fig 2.6 schematic diagram of a SVC

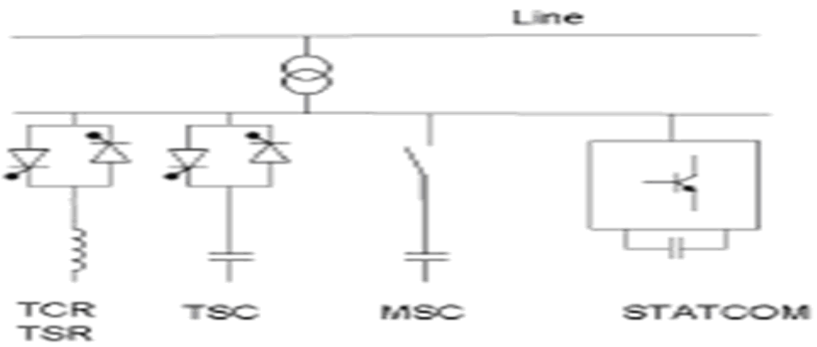


Fig 2.7 Examples of FACTS for shunt compensation

It is supposed that the rating of the shunt FACTS device is large enough to supply the reactive power required to maintain a constant voltage magnitude at bus m and the device does not absorb or supply any active power.

3 .*OUT PUT WAVEFORMS:*

For a simplified model, when there is no FACTS device connected to the line, maximum power transfer through the line is given by [3]:

P = Pm sin s

Many researchers established that the optimal location of shunt FACTS device for a simplified model is at K= 0.5 when there is no series compensation in the line. For such cases maximum power transmission capability (Pm) and maximum transmission angle (δ m) become double. However, for an actual line model power flow is given by Eqs. (4) and (6) instead of Eq. (9) and the above results may not be considered accurate. One of the objectives of this paper is to find the maximum power and corresponding location of shunt FACTS device for different series compensation levels (%S) located at the centre of the line.

A sophisticated computer program was developed to determine the various characteristics of the system using an actual model of the line sections. The constant of the same RE power of section (1) and SE power of section (2) (P r1 = P s2) is incorporated into the problem. In all cases, V s = Vr = Vm = 1.0 p.u. unless specified. The maximum power Pm and corresponding angle δm are prior determined for various values of location (K). Figures 4.4-4.7 show the variation in maximum RE power(pmr), maximum sending end power, and transmission angle (δm) at the maximum sending end power, respectively, against (K) for different series compensation levels (%S) It can be noticed from Figures 4.5and 4.6 that pms> p mr for any series compensation level (%S) because of the loss in the line. From Figure 5 it can be noted that when %S = 0 the value of P ms increases as the value of (K) is increased from zero and reaches the maximum value of 18.5 p.u. at K = 0.45 (but not at K = 0.5). Slope of the p m s curve suddenly changes at K= 0.45 and the value of Pms decreases when K > 0.45.

A similar pattern for Pm rbe observed from Figure 6 when (%S = 0). When series compensation in the line is taken into account, we observe that the optimal location of the shunt FACTS device will change and shifts towards the generator side. As seen from Figure 5, when %S = 15 then Pms increases from 12.5 p.u. (at K = 0) to its maximum value 22 p.u. (at K = 0.375).When K is further increased then Pms decreases. It means that, for maximum power transfer capability, the optimal location of the shunt device will change when series compensation level changes. When %S = 30, the optimal location further shifts to the generator side and P^{m}_{s} increases from 15.2 p.u. (at K = 0) to its maximum value 26.8 p.u. (at K = 0.3).

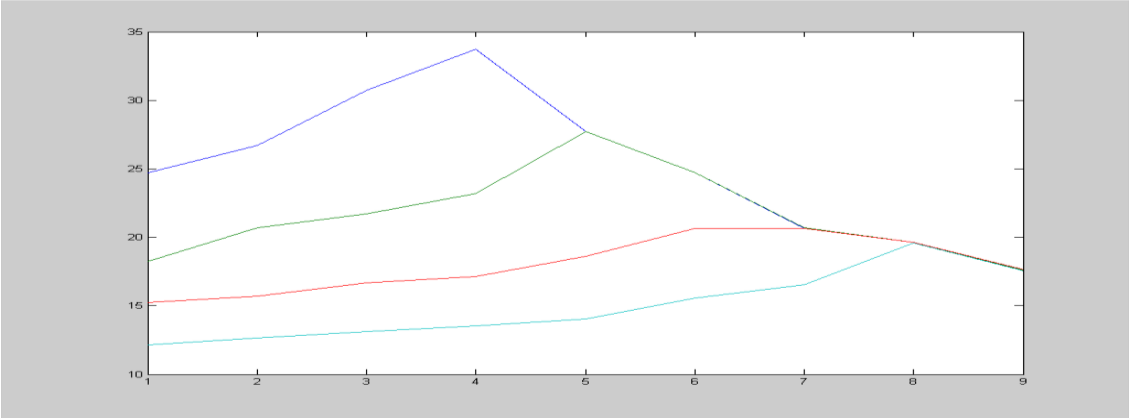


Fig 3.1 Variation in maximum SE power for diff. value of %S.

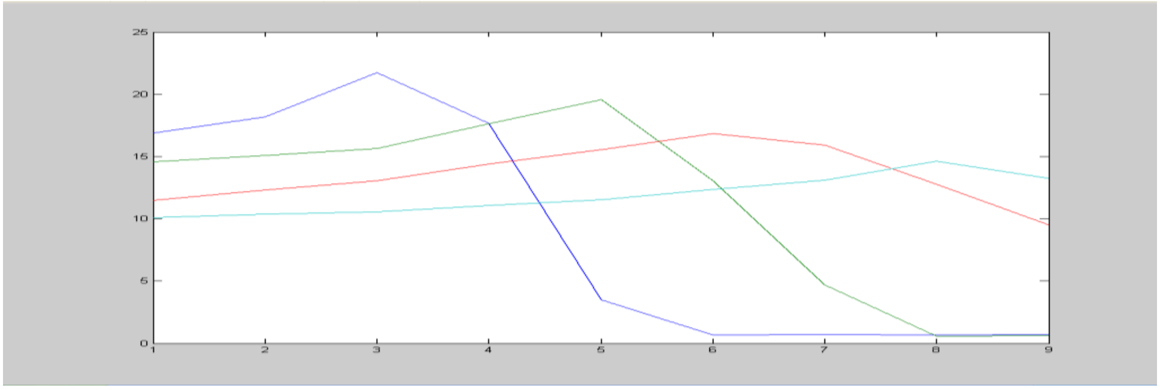


Fig 3.2 Variation in maximum RE power for diff. value of %S.

Similarly, when %S = 45, we obtain the optimal location of the shunt device at K = 0.225. A similar pattern for P^{m}_{r}can be observed from Figure 6 for different series compensation levels. In Figure 7, it can be observed that in the absence of series compensation (%S = 0) the angle at the maximum SE power increases from 95.8o at K = 0 to its maximum value 171.1o at K = 0.45. When %S = 15 then ð^{m}when K is increased and reaches its maximum value 180.5o at K = 0.375. When %S = 30 then δ^{m} increases when K is increased and reaches its maximum value 185o at K = 0.3 and for %S= 45 it is 188o for K = 0.225. As the degree of series compensation level (%S) increases, the stability of the system increases and the optimal location of the shunt FACTS device changes.

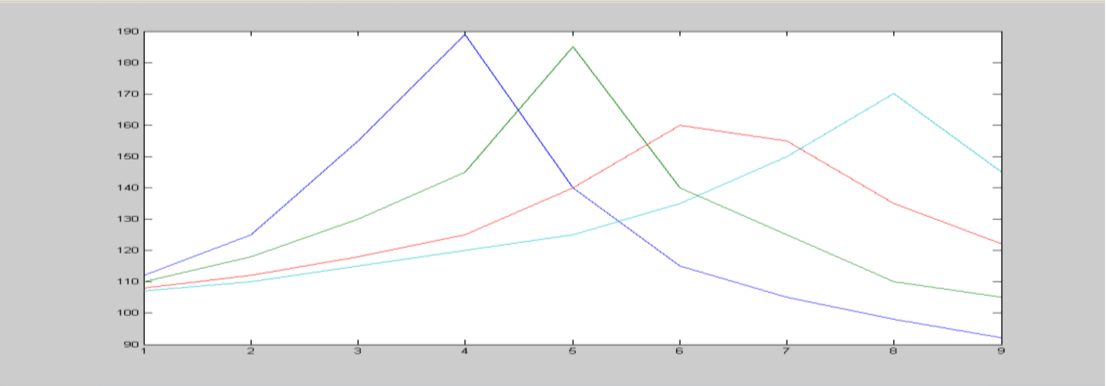


Fig 3.3 Variation in transmission angle at the max. SE power for diff. % S.

Figure 8 shows the variation of the maximum RE power of section 1 (PR1m) and maximum SE power of section 2 (PS2m) against the value of K for different series compensation levels (%S). It can be seen in Figure 8 that for an uncompensated line then maximum power curves cross at K = 0.45 and the crossing point is the transition point.

Thus, to get the highest benefit in terms of maximum power transfer capability and system stability, the shunt FACTS device must be placed at K = 0.45, which is slightly off- centre. When the series compensation level is taken into account then for %S = 15 the maximum power curves cross at K = 0.375 and maximum power transfer capability increases. It means that when series compensation level (%S) is increased then the optimal location of the shunt device shifts towards the generator side. Similarly when %S = 30 then the optimal location is at K = 0.3 and for %S = 45it is at K = 0.25.

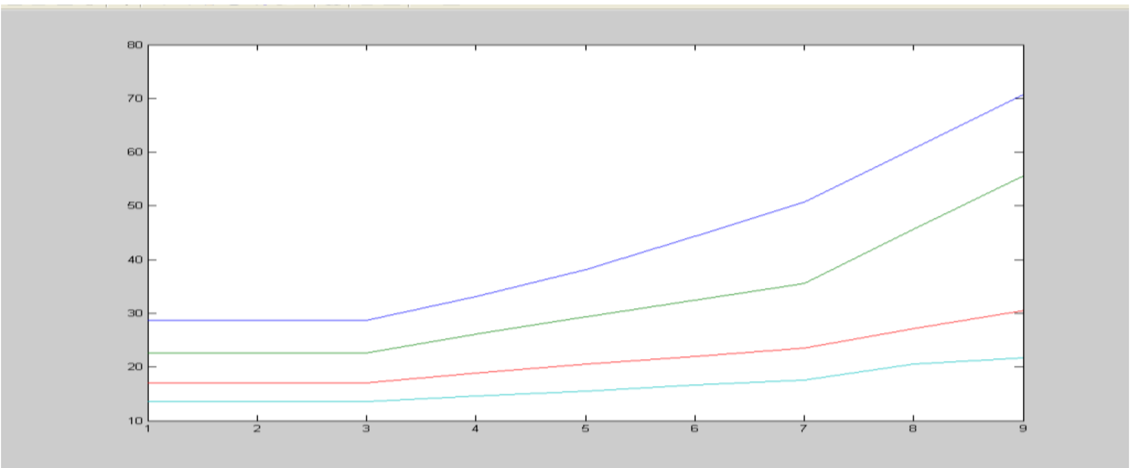


Fig 3.4 Variation in the maximum RE power of section-1 and SE power of section-2 against k for diff. value of %S.

CONCULSION

This paper investigates the effect of series compensation on the optimal location of a shunt FACTS device to get the highest possible benefit of maximum power transfer and system stability. Various results were found for an actual line model of a series compensated 345 kV, 450 km line. It has been found that the optimal location of the shunt FACTS device is not fixed as reported by many researchers in the case of uncompensated lines but it changes with the change in degree of series compensation. The deviation in the optimal location of the shunt FACT device from the centre point of line depends upon the degree of series compensation and it increases almost linearly from the centre point of the transmission line towards the generator side as the degree of series compensation (%S) is increased. Both the power transfer capability and stability of the system can be improved much more if the shunt FACTS device is placed at the new optimal location instead of at the mid-point of the line. The effect of SVC and STATCOM controllers in enhancing power system stability has been examined. Though both the devices can provide extra damping to the system, it has been demonstrated that STATCOM is very effective in enhancing system performance in situations where system voltages are very much depressed. Also, because of its fast response time, STATCOM control is superior to that of SVC.

ACKNOWLEDGEMENTS

I Thank to our college principal Dr. TVV Sudhakar for his kind permission and encouragement to write research paper. Also I am very much thankful to our college Chairman Mr. Kishore Jadwani, vice chairman Mr. Vijay Jadwani, Secretary Mr. Harjeet Singh Hura for providing creative environment for this work. I would like to extend my heartfelt thanks to my colleagues. And finally I am very much obliged to my respected parents who inspiring me around the clock.

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