Optimal Placement of FACTS Device in a Series Compensated Long Transmission Line System

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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 center. As one of the most promising FACTS devices in terms of its ability to control power system quantities, UPFC Effect of change in the 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.**

***IndexTerms*— FACTS, Series compensation, Transmission line system, optimal placement.**

I. 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 [1].

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. 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.

In series compensation, the FACTS Sis connected in series with the power system. It works as a controllable voltage source. Shunt compensation, the power system is connected in shunt with FACTS [2]. It works as a controllable current source. The rating of a shunt FACT device is selected in such a way so as to control the voltage equal to sending end voltage at the bus of the shunt FACT device. A series capacitor is placed at the center to get the maximum power transfer capability and compensation efficiency for the selected rating of the shunt FACTS device. The shunt FACTS device is operated at that rating that is able to control the bus voltage of shunt FACTS device equal to sending end voltage so as to get the maximum possible benefit of maximum power transfer and stability under steady state conditions.

Thus, to get the highest benefit in terms of maximum power transfer capability and system stability, the shunt FACTS device must be placed at slightly off- center. The deviation in the optimal location of the shunt FACT device from the center point of the line depends upon the degree of series compensation and it increases almost linearly from the center point of the transmission line towards the generator side as the degree of series compensation (%S) is increased [3]. 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.

II. TRANSMISSION LINE MODEL

In this study, it is considered that the transmission line parameters are uniformly distributed and the line can be modeled by a 2-port, 4-terminal networks as shown in Fig. 1. This figure represents the actual line model [4].
The relationship between sending end (SE) and receiving end (RE) quantities of the line can be written as Eq. 1 and 2.

$$V_S = AV_R + BI_R \tag{1}$$

$$I_S = CV_R + DI_R \tag{2}$$

The ABCD constants of a line of length l, having a series impedance of z Ω/km and shunt admittance of y S/km, are given by Eq. 3

$$A = D = Cosh(\lambda l)$$
$$B = Z_C Sinh(\lambda l)$$
$$C = Sinh(\lambda l)/ Z_C \qquad (3)$$

Where $\gamma = \sqrt{zy}$ and $Z_C = \sqrt{\frac{z}{y}}$

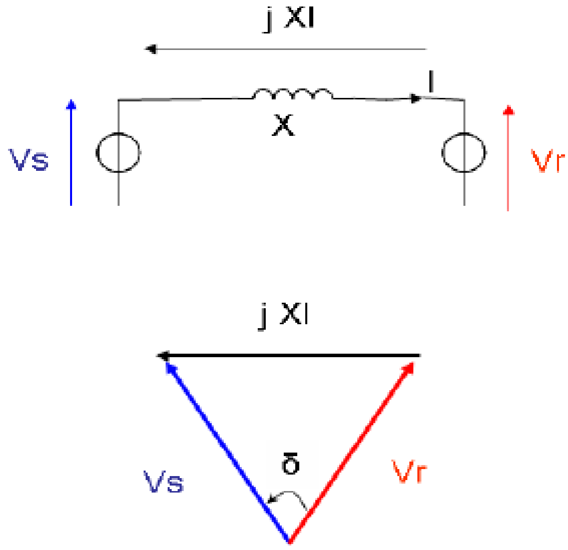

Fig. 1 Series compensation.

The active and reactive power flows at the SE and RE of the line can be written as

$$P_S = C_1 Cos(\beta - \alpha) - C_2 Cos(\beta - \delta) \qquad (4)$$
$$Q_S = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta - \delta) \qquad (5)$$
$$P_R = C_2 Cos(\beta - \alpha) - C_3 Cos(\beta - \delta) \qquad (6)$$
$$Q_R = C_2 \sin(\beta - \alpha) - C_3 Cos(\beta - \delta) \qquad (7)$$

Where $C_1 = AV_S^2 / B$

$$C_2 = V_S V_R / B$$
$$C_3 = AV_R^2 / B$$
$$A = A\angle\alpha,\ B = B\angle\beta$$
$$V_R = V_R\angle 0,\ V_S = V_S\angle\delta$$

It is clear from the equation that the RE power reaches the maximum value when the angle δ becomes β. However, the SE power Ps becomes maximum at δ = (Π− β). In this study, a 345 kV single circuit transmission line (450km in length), is considered. It is assumed that each phase of the line has a bundle of 2 conductors of size one million c-mils each and conductors are fully transposed [5]. The series impedance and shunt admittance of the line are found to be Z = (0.02986 + j0.2849) Ω/km and y = j3.989 × 106 S/km, respectively, at 50 Hz. The parameters are obtained using the PSCAD/EMTDC software package. The results of the line are presented in p.u. on a 100 MVA, 345 kV base.

III. 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 a series capacitor at center and a shunt FACT device at point 'm' as shown in Fig. 2.

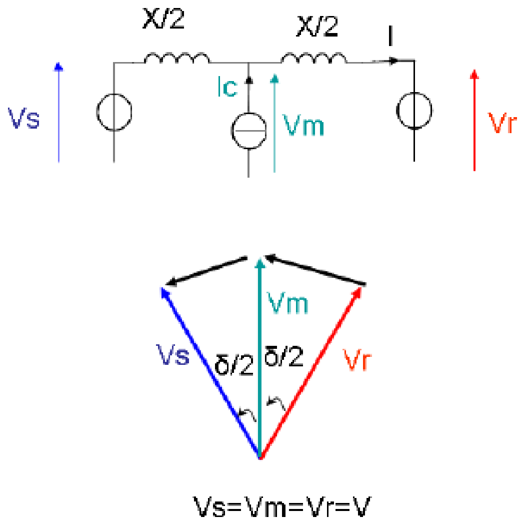

Fig. 2 Shunt compensation

Parameter k is used to show the fraction of the line length at which the FACTS device is placed [6]. The shunt FACTS device may be an SVC or STATCOM and is usually connected to the line through a step-down transformer as shown in Fig. 3 and Fig. 4.

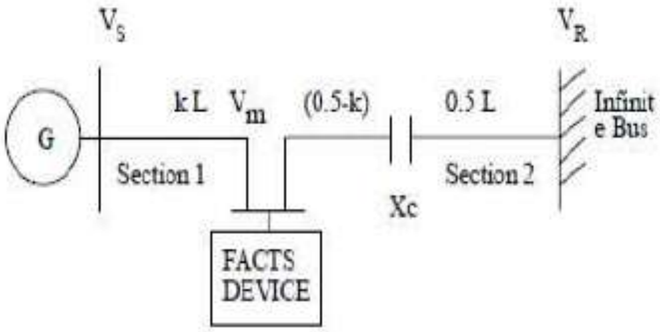

Fig. 3 2-Port, 4-terminal model of a transmission line

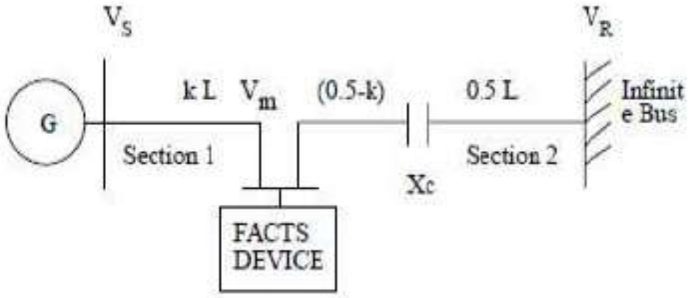

Fig. 4 Series-compensated transmission line with a shunt FACT device

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 with its own ABCD constants considering the actual line model [7]. 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.

IV. MAXIMUM POWER TRANSFER CAPABILITY

For a simplified model, when there is no FACTS device connected to the line, maximum power transfer through the line is given by Eq. 8.

$$P = P_m \sin\delta \qquad (8)$$

Many researchers established that the optimal location of the 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 (δm) become double [8]. However, for an actual line model power flow is given by equations 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 the shunt FACTS device for different series compensation levels (%S) located at the center of the line.

A sophisticated computer program was developed to determine the various characteristics of the system of the Fig. 5 using an actual model of the line sections. The constant of the same RE power of section (1) and SE power of section (2) (PR1 = PS2) is incorporated into the problem. In all cases, VS = 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 show the variation in maximum RE power $\left(P_R^m\right)$, maximum sending end power, and transmission angle δ^m at the maximum sending end power, respectively, against (K) for different series compensation levels (%S). It can be noticed from Figures that $P_S^m \rangle P_R^m$ for any series compensation level (%S) because of the loss in the line [9]. From Figure, it can be noted that when %S = 0 the value of $\left(P_S^m\right)$ 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). The slope of the $\left(P_S^m\right)$ curve suddenly changes at K= 0.45 and the value of $\left(P_S^m\right)$ decreases when K >0.45 [10]. A similar pattern for $\left(P_R^m\right)$ can be observed from figure 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 the figure, when %S = 15 then $\left(P_S^m\right)$ increases from 12.5 p.u. (at K = 0) to its maximum value 22 p.u. (at K = 0.375).

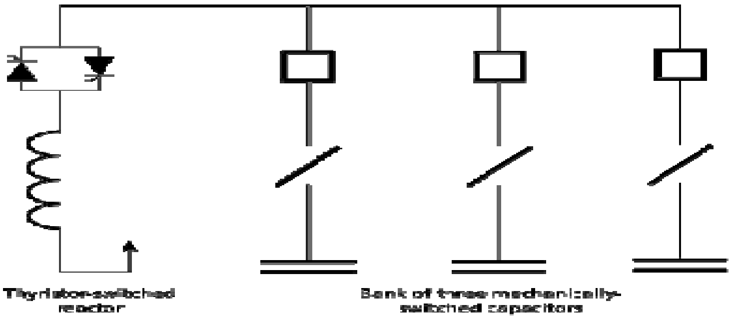

Fig. 5 Schematic diagram of an SVC

When K is further increased then $\left(P_S^m\right)$ 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 $\left(P_S^m\right)$ increases from 15.2 p.u. (at K = 0) to its maximum value26.8 p.u. (at K = 0.3).Similarly, when %S = 45, we obtain the optimal location of the shunt device at K = 0.225. A similar pattern for $\left(P_S^m\right)$ can be observed from Fig. 6 for different series compensation levels [11].

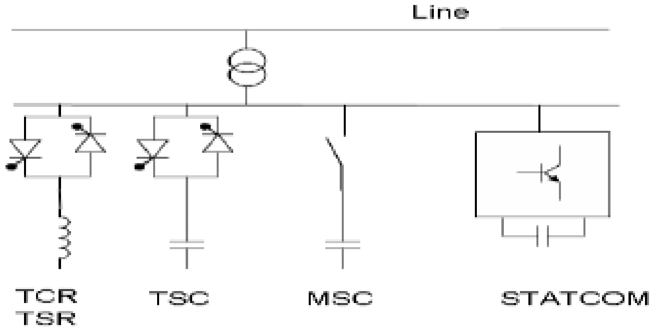

Fig. 6 Examples of FACTS for shunt compensation

In Fig. 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 δm increases when K is increased and reaches its maximum value 180.5o at K = 0.375. When %S = 30 then δm 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 [12].

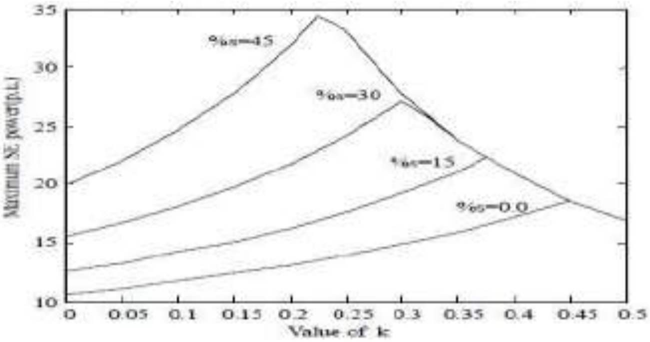

Fig. 7 Variation in maximum SE power for diff. the value of %S

V. OPTIMAL LOCATION OF SHUNT FACTS DEVICES

The Fig. 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 that for an uncompensated line then maximum power curves cross at K = 0.45 and the crossing point is the transition point.

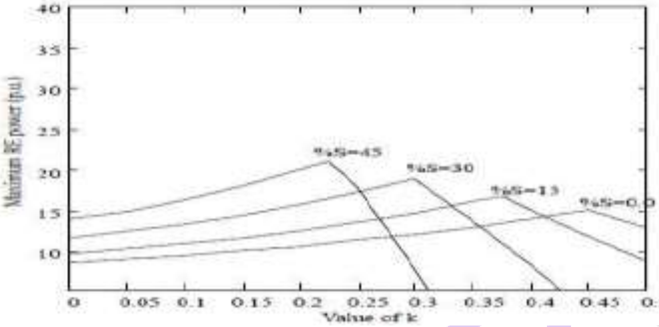

Fig. 8 Variation in maximum RE power for diff. the value of %S

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- center. 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 = 45 it is at K = 0.25. The Fig. 9 shows the variation in the optimal off-center location of the shunt FACTS device against the degree of series compensation level (%S) for the given R/X ratio of the line. It can be observed in Figure that the optimal off-center location is 10% for the uncompensated line. When series compensation level (%S) is increased than optimal off-center location increases linearly and reaches its highest value 55% for %S = 45. The operation of the UPFC demands proper power rating of the series and shunt branches. The rating should enable the UPFC carrying out pre-defined power flow objective.

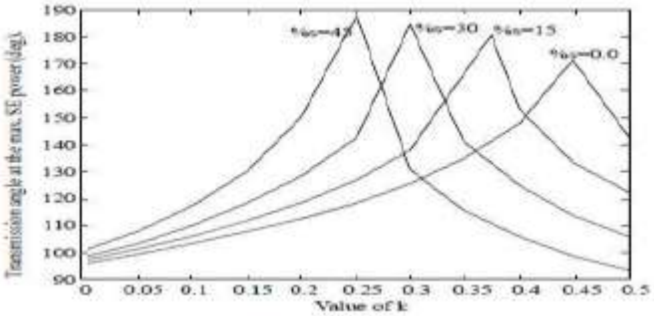

Fig. 9 Variation in transmission angle at the max. SE power for diff. %S

VI. SIMULATION RESULTS AND DISCUSSION

The performance of the proposed concept of optimal placement of shunt connected facts device in a series compensated long transmission line has been evaluated by simulation as shown in Fig. 10. The performances of the proposed system are shown in the Fig. 11 to Fig. 15 under different conditions.

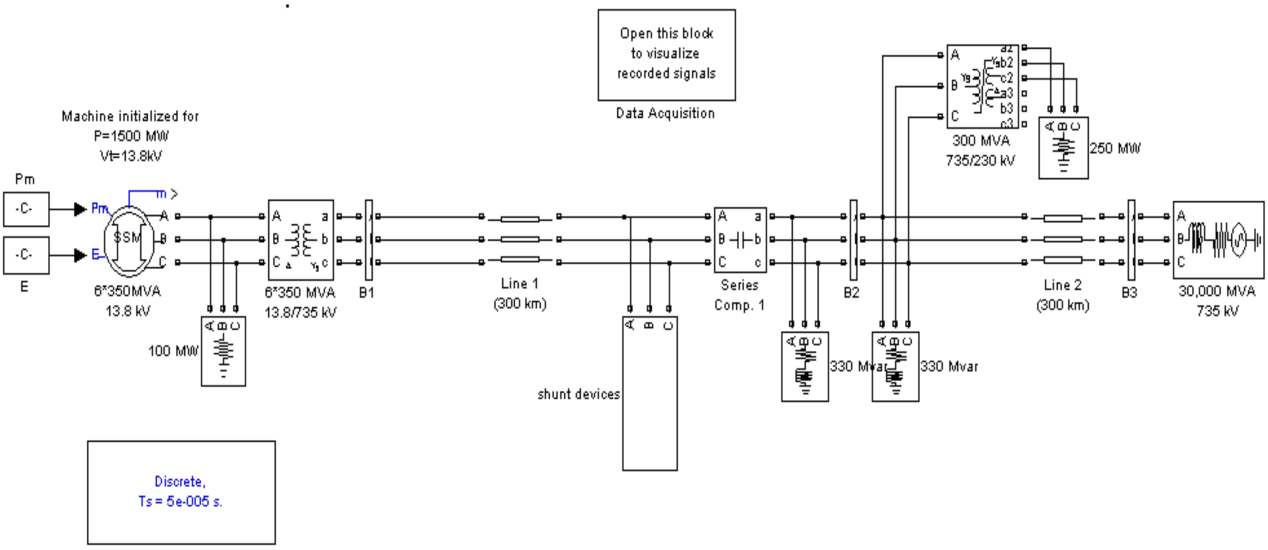

Fig. 10 MATLAB/Simulink Model of proposed system

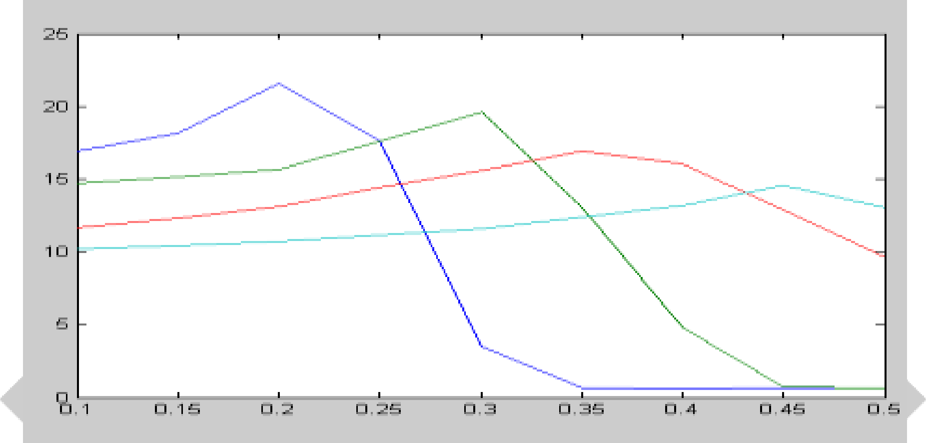

Fig. 11 Variation in maximum RE power for diff. the value of %S

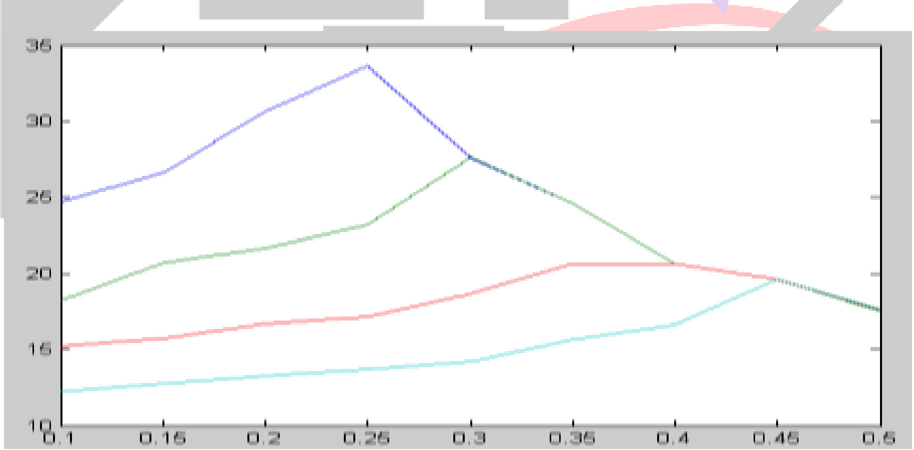

Fig. 12 Variation in maximum SE power for diff. the value of %S

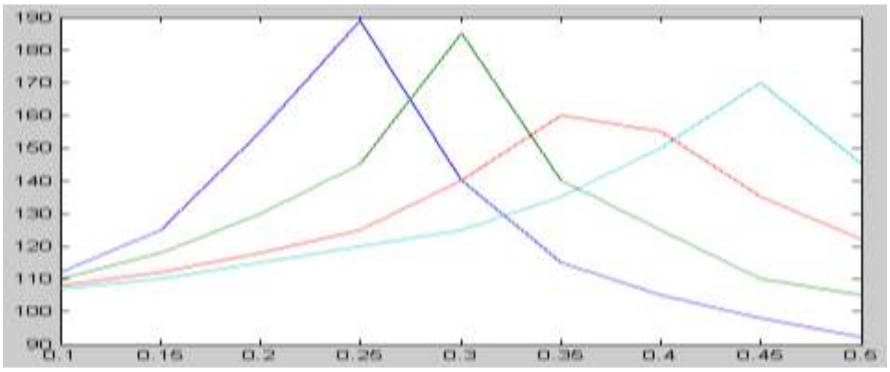

Fig. 13 Variation in transmission angle at the max. SE power for diff. %S

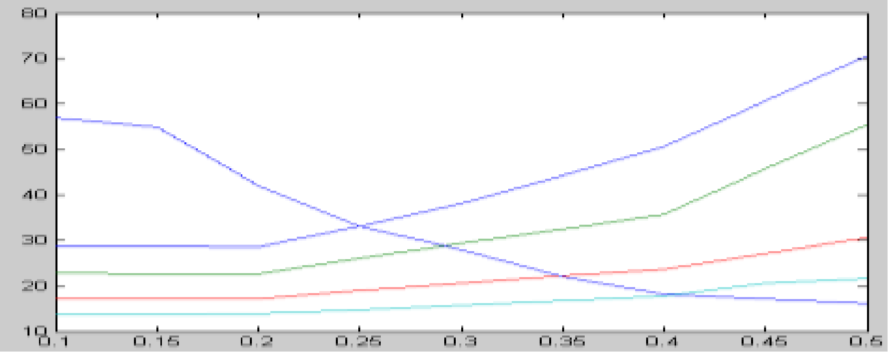

Fig. 14 Variation in the maximum RE power of section-1 and SE power of section-2 against k for diff. the value of %S

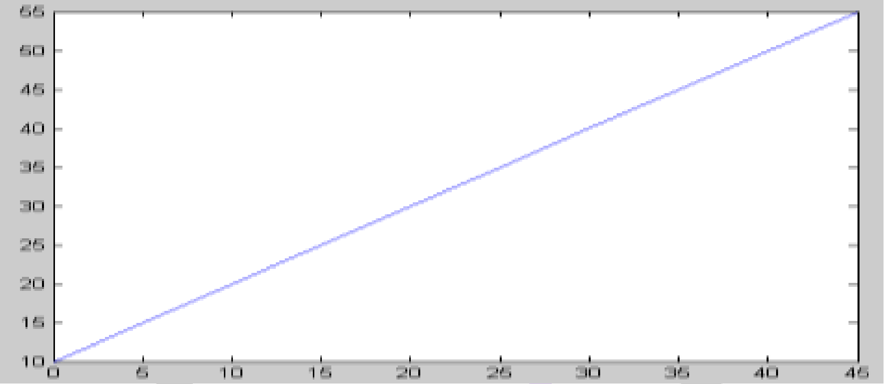

Fig. 15 Variation in the optimal off-center location of the shunt FACTS device against the degree of compensation of line (%S)

VI. CONCLUSION

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 the degree of series compensation. The deviation in the optimal location of the shunt FACT device from the center point of the line depends upon the degree of series compensation and it increases almost linearly from the center 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.

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