Optimal Location for Shunt Connected FACTS Devices in a Series Compensated Long Transmission Line

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Abstract

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. Effect of change in degree of series compensation on the optimal location of the shunt FACTS device to get the highest possible benefit is studied. It is found that the optimal location of the shunt FACTS device varies with the change in the level of series compensation to get the maximum benefit in terms of power transfer capability and stability of the system.

Key Words: *Maximum receiving end power, shunt FACTS, degree of series compensation, transmission angle, optimal location.*

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 devices can be connected to a transmission line in various ways, such as in series, shunt, or a combination of 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. The term and definition of various FACTS devices are described in references [1,9].

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, insofar as thermal limits permit, while maintaining the same degree of stability [7,11].

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 [5,8,11]. With the widespread and active consideration of the installation of FACTS controllers for better controllability in power systems, appropriate placement of these devices is becoming important. Improperly placed FACTS controllers fail

to give the optimum performance and can even be counterproductive. Therefore, proper placement of these devices must be examined.

This paper investigates the optimal location of shunt FACTS device in a series compensated transmission line to get the maximum possible benefit of maximum power transfer and system stability. 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. It is observed that the optimal location of a shunt FACT device deviates from the center of the line towards the generator side with the increase in the degree of series compensation (%s) and is not fixed as reported in reference [7]. 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 FACT device. The shunt FACT device is operated at that rating that is able to control the bus voltage of shunt FACT device equal to sending end voltage so as to get the maximum possible benefit of maximum power transfer and stability under steady state conditions.

2.   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 Figure 1. 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:
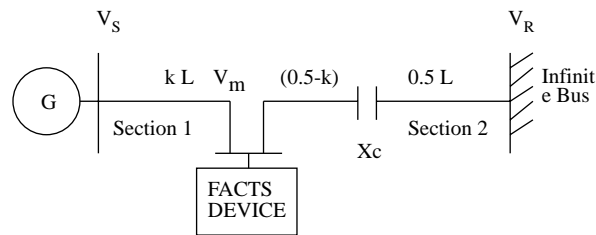

Figure 1. Two-pPort, 4-terminal model of a transmission line [7].

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

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

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

$$A = D = \cosh(\gamma l) \qquad B = Z_C \sinh(\gamma l)$$

$$C = \sinh(\gamma l)/Z_C \qquad \text{where } \gamma = \sqrt{zy} \qquad \text{and } Z_C = \sqrt{z/y}$$

The active and reactive power flows at the SE and RE of the line can be written as [7]

$$P_S = C_1 \cos(\beta - \alpha) - C_2 \cos(\beta + \delta) \tag{4}$$

$$Q_S = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta + |\delta) \tag{5}$$

$$P_R = C_2 \cos(\beta - \delta) - C_3 \cos(\beta - \alpha) \tag{6}$$

$$Q_R = C_2 \sin(\beta - \delta) - C_3 \cos(\beta - \alpha) \tag{7}$$

where $C_1 = A\, Vs^2/B$, $C_2 = VsV_R/B$, $C_3 = A\, V_R^2/B$ and $A = A \angle \alpha$, $B = B \angle \beta$ $V_R = V_R \angle\, 0$, $Vs = Vs \angle \delta$

It is clear from Eq. (6) that the RE power reaches the maximum value when the angle δ becomes β. However, the SE power P_S of Eq. (4) becomes maximum at $\delta = (\Pi - \beta)$. In this study, a 345 kV single circuit transmission line (450 km in length), is considered. It is assumed that each phase of line has a bundle of 2 conductors of size one million c-mils each and conductors are fully transposed. The series impedance and shunt admittance of the line are found to be $Z = (0.02986 + j0.2849)$ Ω/km and $y = j3.989 \times 10^6$ 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 [7].

2.1.   Series Compensated Transmission Line with Shunt Fact Device

Consider that the line is transferring power from a large generating station to an infinite bus and equipped with
series capacitor at center 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 and 4. 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.
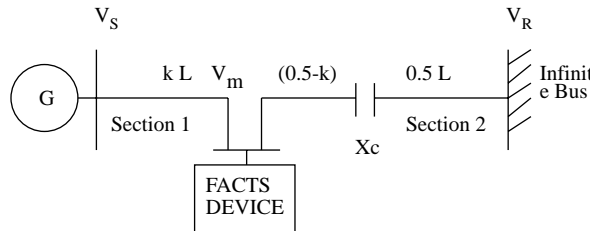

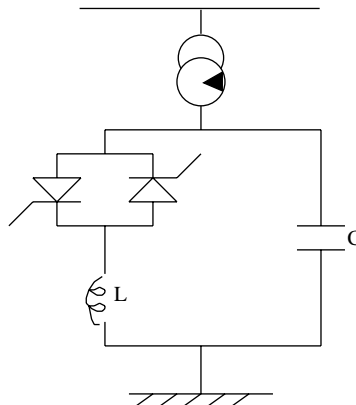**Figure 2.** Series compensated transmission line with a shunt FACT device [7].

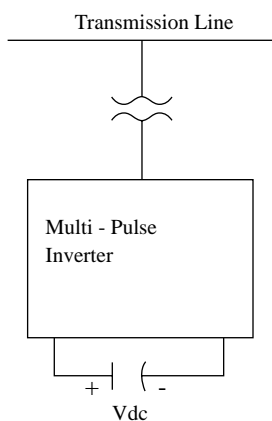**Figure 3.** Schematic diagram of a SVC [7].

Figure 4. Shunt Connected FACT devices STATCOM [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.

3. 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 [7]:

$$P = P_m \sin \delta \qquad (9)$$

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 (P^m) 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 center of the line. A sophisticated computer program was developed to determine the various characteristics of the system of Figure 2 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, $V_S = V_R = V_M$ = 1.0 p.u. unless specified. The maximum power P^m and corresponding angle δ^m are prior determined for various values of location (K). Figures 5-7 show the variation in maximum RE power (P_R^m), 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 5 and 6 that $P_S^m > P_R^m$ 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_S^m 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_S^m curve suddenly changes at K= 0.45 and the value of P_S^m decreases when K > 0.45. A similar pattern for P_R^m can be 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 P_s^m 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 P_S^m 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_S^m increases from 15.2 p.u. (at K = 0) to its maximum value 26.8 p.u. (at K = 0.3).
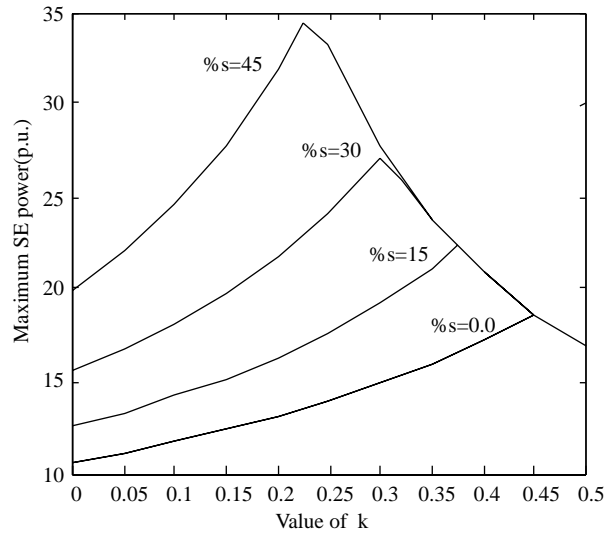

Figure 5. Variation in maximum SE power for diff. value of %s.

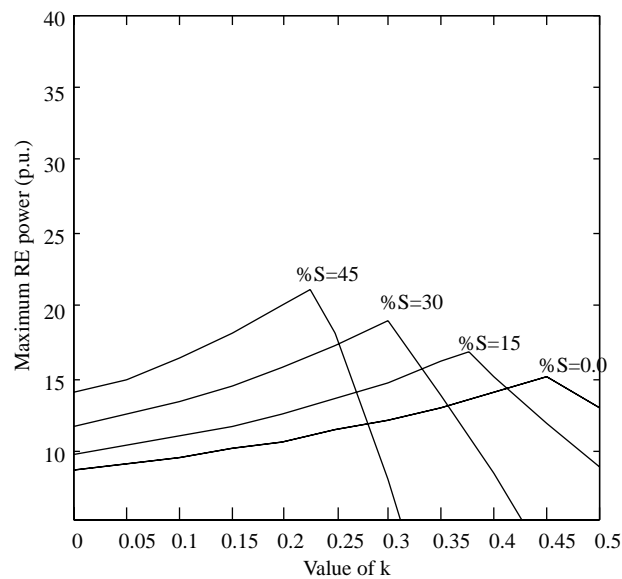**Figure 6.** Variation in maximum RE power for diff. value of %S.

Similarly, when %S = 45, we obtain the optimal location of the shunt device at K = 0.225. A similar pattern for P_R^m 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 95.8° at K = 0 to its maximum value 171.1° at K = 0.45. When %S = 15 then δ_m increases when K is increased and reaches its maximum value 180.5° at K = 0.375. When %S = 30 then δ_m increases when K is increased and reaches its maximum value 185° at K = 0.3 and for %S =

45 it is 188° 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.
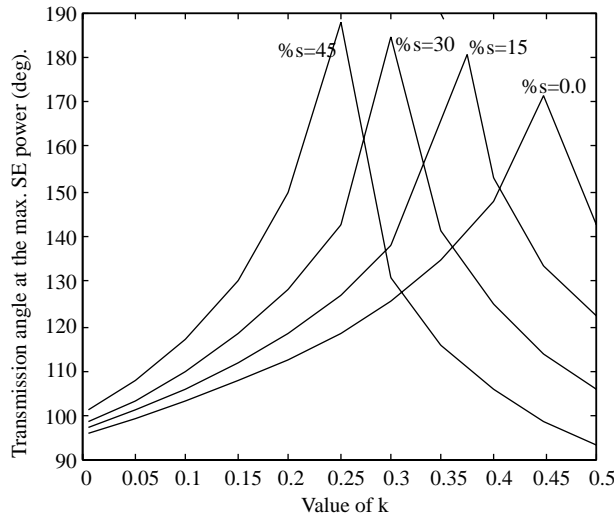

Figure 7. Variation in transmission angle at the max. SE power for diff. %s.

4. Optimal Location of Shunt Facts Devices

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.
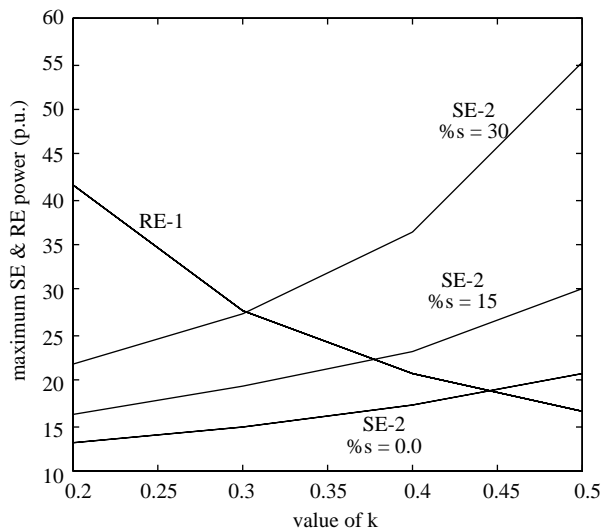

Figure 8. Variation in the maximum RE power of section-1 and SE power of section-2 against k for diff. value of %S.

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. Figure 9 shows the variation in 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 9 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.
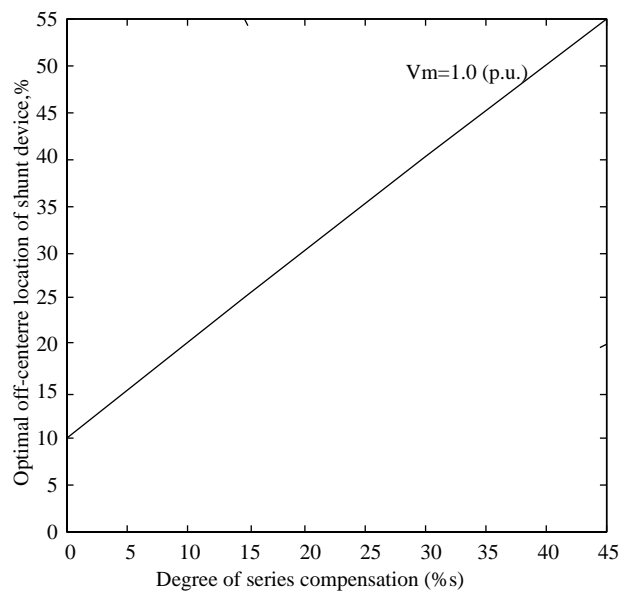

Figure 9. Variation in the optimal off-center location of shunt FACTS device against degree of compensation of line (%S).

5. 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 degree of series compensation. The deviation in the optimal location of the shunt FACT device from the center point of 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.

References

[1] A.A. Edris, R. Aapa, M.H. Baker, L. Bohman, K. Clark, "Proposed terms and definitions for flexible ac transmission systems (FACTS)", IEEE Trans. on power delivery, Vol. 12, No. 4, pp. 1848-1853, 1997.

[2] M. Noroozian, Languist, M. Ghandhari, G. Anderson, "Improving power system dynamics by series connected FACTS devices", IEEE Trans. on Power Delivery, Vol. 12, No. 4, pp. 1635-1641, 1997.

[3] K.R. Padiyar, R.K. Verma, "Concepts of static VAR System control for enhancing power transfer in long transmission lines", Electric Machines and Power Systems, Vol. 18, pp. 337-358, 1990.

[4] N. Kumar, A. Ghosh, R.K. Verma, "A novel placement strategy for FACTS controllers", IEEE Trans. on Power Delivery, Vol. 18, No. 3, pp. 982-987, 2003.

[5] A.E. Hammad, "Analysis of power system stability enhancement by static var compensators", IEEE Trans. on Power Systems, Vol. 1, No. 4, pp. 222-227, 1986.

[6] R. Mohan Mathur, R.K. Verma, Thyristor Based FACTS Controllers for Electrical Transmission Systems, New York, Wiley, 2002.

[7] M.H. Haque "Optimal location of shunt FACTS devices in long transmission line", IEE Proceedings on Generation Transmission & Distribution, Vol. 147, No. 4, pp. 218-22, 2000.

[8] M. Noroozian, G. Andersson, "Damping of power system oscillations by the use of controllable components", IEEE Trans. on Power Systems, Vol. 9, No. 4, pp. 2046-2054, 1994.

[9] N.G. Hingorani, L. Gyugyi, Understanding FACTS, Concept and Technology of Flexible AC Transmission Systems, New York, Wiley, 2000.

[10] B.T. Ooi, M. Kazerrani, R. Marceau, Z. Wolanski "Mid point siting of FACTS devices in transmission lines", IEEE Trans. on Power Delivery, Vol. 12, No. 4, pp. 1717-1722, 1997.

[11] P. Kundur, Power system stability and control, EPRI Power System Engineering Series, New York, McGraw-Hill Inc., 1994.