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Enhancement of Power Flow with optimum location of Shunt connected Facts Device in series compensated Long transmission lines

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***Abstract*— The flexible AC transmission system (FACTS) in a power system plays a vital role in improving the power system performance, both the static and dynamic, where improving the stability, reducing the losses and the cost of generation, also enhancing the system loading capability with rerouting the power flow in the network. In order to reach the above goals, these devices must be located optimally. 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 degree of series compensation on the optimal placement of the shunt FACTS device to get the highest possible benefit is studied. In MATLAB/SIMULINK the results obtained shown that\ optimal placement of the shunt FACTS device varies with the change in the level of series compensation.**

***Index Terms*— FACTS, optimal location, Power flow, UPFC.**

I. Introduction

In this decade with the deregulation of the electricity market, the traditional concepts and practices of power systems are changed. This led to the introduction of FACTS devices such as static VAR compensator (SVC), thyristor controlled series compensation (TCSC), thyristor controlled phase angle regulator (TCPR) and unified power flow controller (UPFC). These devices controls the power flow in the network, reduces the flow in heavily loaded lines there by resulting in an increase load ability, low system losses, improved stability of network and reduced cost of production [1], It is important to ascertain the location of these devices because of their significant costs provides an idea regarding the optimal locations of fact devices, without considering the investment cost of FACTS device and their impact on the generation cost.

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The generation cost of the power plants and investment cost of the devices, discussed optimal location problem by power loss reduction. The different types of FACTS devices and their different location have different advantages. In realizing, for the proposed objective function, the suitable types of FACTS device, their location, and their rated value must be determined simultaneously.

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].

Shunt compensation is of two types:
Shunt capacitive compensation: This method is used to improve the power factor. Whenever an inductive load is connected to the transmission line, power factor lags because of lagging load current. To compensate, a shunt capacitor is connected which draws current leading the source voltage. The net result is improvement in power factor.

Shunt inductive compensation:
This method is used either when charging the transmission line, or, when there is very low load at the receiving end. Due to no load very low current flows through the transmission line, Shunt capacitance in the transmission line causes voltage amplification (Ferranti Effect). The receiving end voltage may become double the sending end voltage (generally in case of very long transmission lines). To compensate, In the case of a no-loss line, voltage magnitude at receiving end is the same as voltage magnitude at sending end: VS = VR=V. Transmission results in a phase lag δ that depends on line reactance X. shunt inductors are connected across the transmission lines.

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.

A series capacitor is placed at the center to get the maximum power transfer capability and compensation

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efficiency for the selected rating of the shunt FACTS device. The shunt FACTS device is operated at that

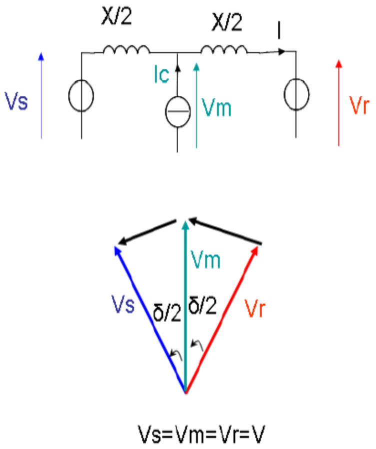

Figure 1: Shunt Compensation.

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.

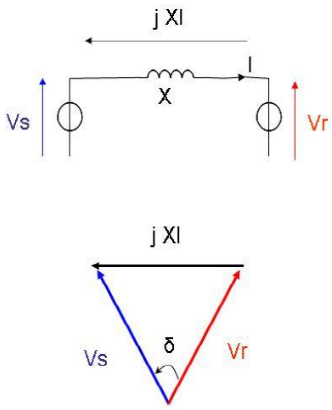

Figure 2: series Compensation.

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.

II. FACT Devices

It is known that the power transfer limit and the quality of supply can be drastically improved by insertion of voltage or current into a power system. This can be achieved by use of power electronics switches and converters. The technology is called Flexible AC Transmission System (FACTS) [1]-[3]. FACTS devices are usually classified into two groups depending on how they generate reactive power:

- Devices which have an inductor or a capacitor as reactive elements being controlled by power electronic switches, e.g. *Static Var Compensator* (SVC), *Thyristor Controlled Series Capacitor* (TCSC),
- Devices in which the reactive power producer is the power electronic converter itself. These devices do not have any capacitors or inductors as reactive power elements. The STATCOM, SCRC and UPFC belong to this category.

According to their application, FACTS devices can be categorized as shunt compensators, series compensators or both shunt-series compensators. Each type of FACTS device has a different impact on the overall system performance [4] (Table 1).

Table 1: Impact of FACTS devices on system performance.

Application	Shunt FACTS Devices	Series FACTS Devices	UPFC
Voltage Control	High	Low	High
Load Flow Control	Low	Medium	High
Transient Stability	Low	High	High
Oscillation Damping	Medium	High	High

III. 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 3. 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:

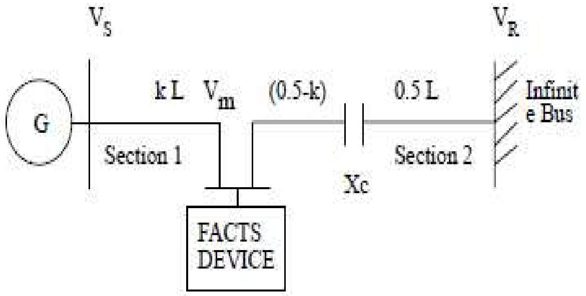

Figure 3: 2-port, 4-terminal transmission line model.

A. Unified Power Flow Concept (UPFC)

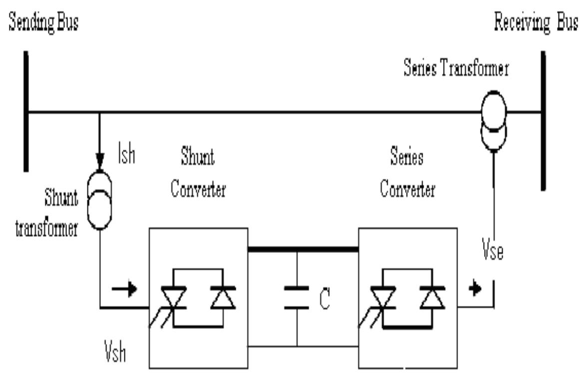

Figure 4: Basic Structure of an UPFC.

The UPFC consists of a series and a shunt converter is connected back-to-back through a common dc link. The shunt converter is connected also in parallel with the line transmission by transformer, allows controls the UPFC bus Voltage/shunt reactive power and the dc capacitor voltage.

B. $V_s = AV_R + BI_R$ (1)

$I_S = CV_R + DI_R$ (2)

The ABCD Constants of a line of length 1, having a series impedance of Z ohm/km and shunt admittance of y S/km, are given by

$$A = D = \cosh(\lambda l) \quad B = Z_c \sinh(\lambda l) \quad C = \sinh(\lambda l)/Z_c \qquad (3)$$

Where $\lambda = \sqrt{Zy}$ and $\sqrt{Z/y}$

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

C. $P_S = C_1\cos(\beta - \alpha) - C_2\cos(\beta - \delta)$ (4)

D. $Q_S = C_1\sin(\beta - \alpha) - C_2\sin(\beta - \delta)$ (5)

E. $P_R = C_2\cos(\beta - \delta) - C_3\cos(\beta - \alpha)$ (6)

F. $Q_R = C_2\cos(\beta - \delta) - C_2\cos(\beta - \alpha)$ (7)

Where

$$C_1 = AV_S^2/B$$
$$C_2 = V_S V_R/B$$
$$C_2 = AV_R^2/B$$
$$A = A\angle\alpha, B = B\angle\beta$$
$$V_R = V_R\angle 0, V_S = V_S\angle\delta$$

It is clear from Eq. (6) that the RE power reaches the maximum value when the angle δ becomes β. However, the SE power PS of Eq. (4) becomes maximum at $\delta = (\Pi - \beta)$. In this study, a 735 kV single circuit transmission line (300 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.

B. **Series Compensated with shunt FACT devices in Transmission**

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

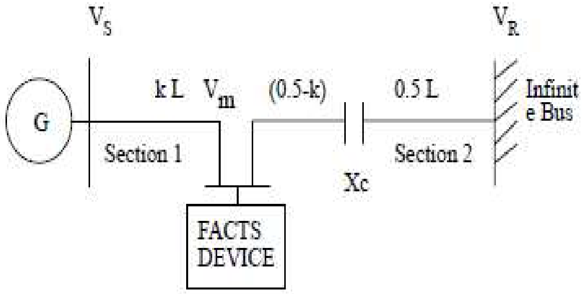

Figure 5: Shunt FACT devices with series compensated transmission line model.

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.

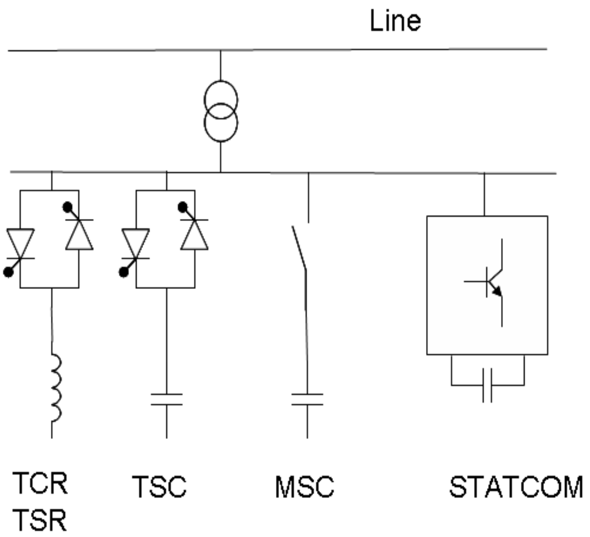

Figure 6: Examples of FACTs devices.

III. 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 [3]:

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

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. (8) 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 5 using an actual model of the line sections.

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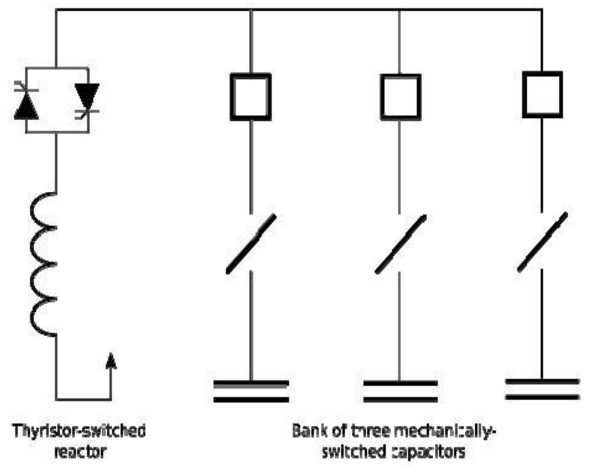

Figure 7: Schematic diagram of SVC.

IV. Modeling and Simulation Results

Figure 8 shows the Modeling of series compensated with shunt FACTs device for optimal location in long transmission line.

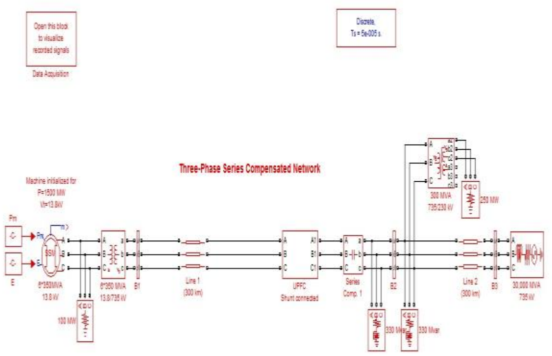

Figure 8: Modelling of Three phase series compensated with shunt FACT devices.

The constant of the same RE power of section (1) and SE power of section (2) (P*R*1 = P*S*2) 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 *δm* are prior determined for various values of location (K). Figures 6-9 show the variation in maximum RE power (P_R^m), 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 6 and 7 that $P_S^m > P_R^m$ for any series compensation level (%S) because of the loss in the line.

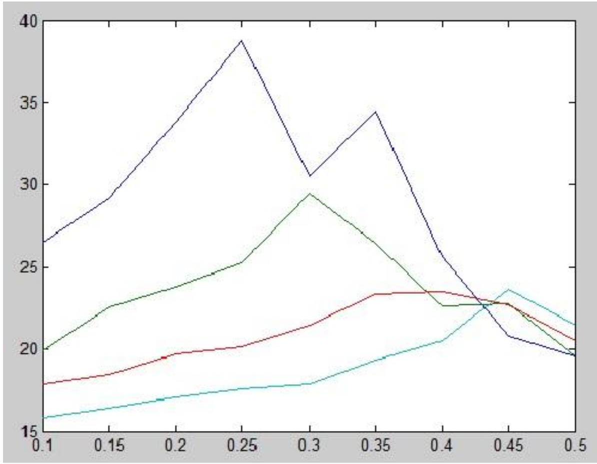

Figure 9: Variation in maximum SE power for diff. value of %S.

From Figure 7 it can be noted that when %S = 0 the value of P_R^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 7, 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).

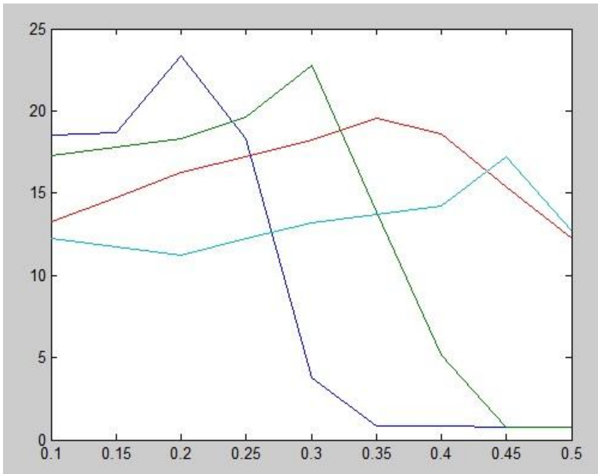

Figure 10: Variation in maximum RE power for diff. value of %S.

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 9, 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

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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.

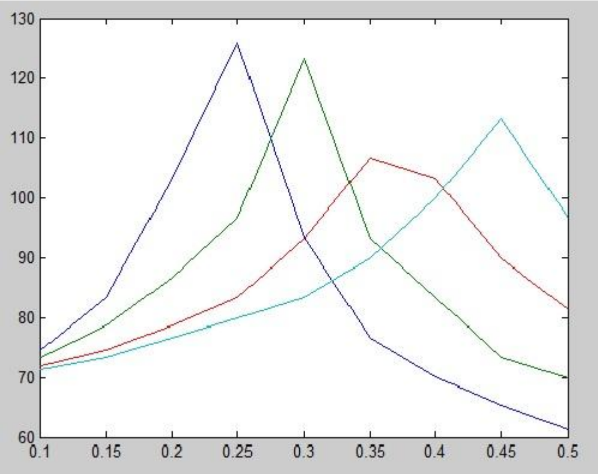

Figure 11: Variation in transmission angle at the max. SE power for diff %S.

Optimal location of Shunt FACT 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.

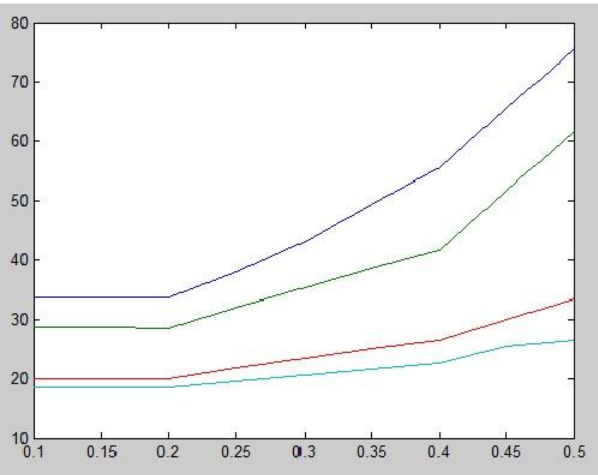

Figure 12: Variation in the maximum RE power of section-1 and SE power of section-2 against k for diff. value of %S.

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.

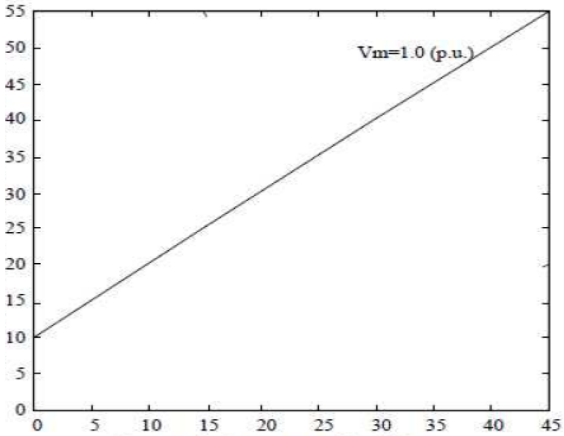

Figure 11: Variation in the optimal off-center location of shunt FACTS device against degree of compensation of line (%S).

Similarly when %S = 30 then the optimal location is at K = 0.3 and for %S = 45 it is at K = 0.25. Figure 12 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 12 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. 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.

V. 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 735 kV, 300 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.

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