International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 8, August - 2013

Optimal Placement of Shunt FACTS in Compensated Transmission Line

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Abstract- *This paper presents detailed analysis of Flexible AC Transmission System (FACTS) i.e. SVC. Effects of location of SVC on the system maximum power transfer including different levels of series compensations present on the system. 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 proposed model is simulated using MATLAB/SIMULINK and results are also presented.*

Index Terms— *FACTS, loadability, SVC, UPFC, voltage collapse.*

1. Introduction

Power systems today are large and complex networks. Day by day there is an increase in the loads connected to the system. This greatly demands transfer of high power through the transmission lines. In-order to achieve this, effective planning and control of the system is required. Due to the resistance and dominant inductive nature of the transmission lines, there is large amount of power loss, voltage drop and reactive power drop. There would be a tremendous increase in the power transfer capability of the existing transmission lines if the operating parameters of the transmission line could be controlled like current, line reactance [1]. This could possibly be achieved by placing capacitances in the transmission system. These non-FACTS devices offer poor voltage regulation and beyond certain level of compensation a stable operating point is unattainable. Fast control of system parameters is not possible using non-FACTS. It is envisaged that a new solution to such problems will rely on the upgrading of existing transmission corridors by using the latest power electronic equipment and methods, a new technological thinking that comes under the generic title of FACTS – an acronym for flexible alternating current transmission systems. FACTS devices not only improve the power transfer capability but also increase the voltage stability. With the improvements in current and voltage handling capabilities of these FACTS devices the possibility has arisen of using different types of controllers for efficient shunt and series compensation. FACTS devices have fast response and the voltage improvement obtained is in a desired range.

It is well known that shunt and series compensation can be used to increase the maximum transfer capabilities of power networks. The ability to control the line impedance and the nodal voltage magnitudes and phase angles at both the sending and the receiving ends of key transmission lines, with almost no delay, has significantly increased the transmission capabilities of the network while considerably enhancing the security of the system. Each of them has its own characteristics and limitations.

All series Controllers inject voltage in series with the line. Even variable impedance multiplied by the current flow through it, representsan injected series voltage in the line. As long as the voltage is in phase quadraturewith the line current, the series Controller only supplies or consumes variable reactivepower. Any other phase relationship will involve handling of real power as well. An example foe series controller is TCSC (Thyristor controlled series compensator). All shunt Controllers inject current into the system at the point of connection. Even variable shunt impedance connected 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. An example foe series controller is SVC (Static VAR compensator).

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 centre of the line towards the generator side with the increase in the degree of series Compensation. A series capacitor is placed at the centre 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.

2. Mathematical model and equations

SVC is a shunt connected FACTS device that helps in controlling and maintaining the specific power system variable by varying its output capacitive current or reactive current. Two widely used models of SVC are the fixed capacitor (FC) with a thyristor controlled reactor (TCR) model and the thyristor switched capacitor (TSC) with TCR. In this paper the FC-SVC model of SVC is used for the analysis [10]. By controlling the Firing angle of the thyristor the fundamental component of the controller current can be varied from its maximum value to the zero. Fig.1 represents the steady-state model of SVC. This effect is equivalent to varying the impedance of the controller [8]. Hence by varying the Firing Angle the current (Lead/Lag) supplied can be varied.

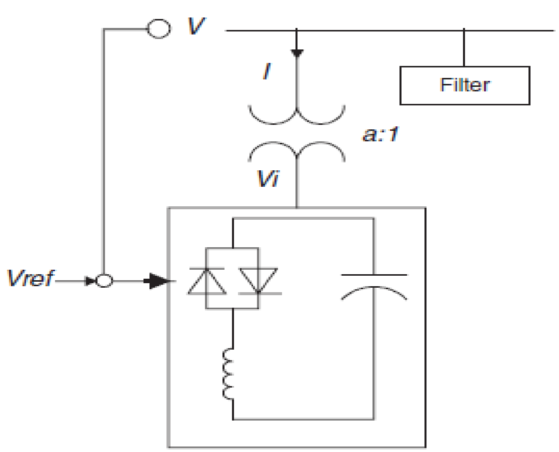


Fig.1 Basic structure of SVC

However several harmonics are produces which can be removed by using a filter tuned at power frequency. Assuming voltage of the controller equal to the bus voltage fundamental component of only TCR current could be obtained by performing Fourier series analysis.

$$I = \frac{V * 2(\Pi - \alpha) + Sin 2\alpha}{\Pi X_l} \quad \text{.......(i)}$$

$$Xv = \frac{X_l * \Pi}{2(\Pi - \alpha) + \sin 2\alpha} \quad \text{.......(ii)}$$

Where,
I= Fundamental component of TCR current
X_l = reactance caused by the fundamental frequency without thyristor control and α is the firing angle.
X_v= Variable reactance of the TCR.
Hence, the total equivalent impedance of the SVC can be represented as:

$$X_e = \left(X_c \frac{\Pi \, 1/r}{\sin 2\alpha - 2\alpha + \Pi(2 - \frac{1}{r})} \right) \quad \text{......(iii)}$$

Xe= Reactance of SVC
Xc=Capacitive reactance

$$r = \frac{X_c}{X_l}.$$

The limits of the controller are given by the firing angle limits which are fixed by design. In-order to have a clear idea about the working of SVC when installed in the power system its steady state V-I characteristics have to be studied. From Fig.2, the operation of SVC can be explained as follows. When the system is operating at normal situation the voltage is at point A.
Increase in Load: When there is any increase in load the current drawn increases due to which voltage drop increases and the receiving end voltage decreases. In-order to improve the voltage profile, reactive power has to be supplied which could be accomplished by the SVC. It has to be controlled in such a way that it supplies net capacitive current providing reactive power and improving the voltage profile. This can be done by firing the thyristors so that they have a maximum value of the Capacitance. Thus the voltage

profile is improved to V_4 drawing the current I_4.Decrease in load: Due to decrease in the load, current drawn decreases and the drop decreases which results in an increase in the receiving end voltage. In-order to maintain voltage at its previous point reactive power has to absorbed, which could be accomplished by using SVC[10]. It has to be operated in such a way that it supplies net lagging current, absorbing the reactive power and decreasing the voltage profile. This can be done by firing the thyristors; so that they include large value of inductance (Assuming Inductance rating is higher than capacitance). Thus the voltage profile is brought back to V_3 by drawing current I_3.

3. Simulation and Results:

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

$$P = P_m \text{Sin}\delta$$

Many researchers have already 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,. 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. Figures 4-6 show the variation in maximum RE power(P^m_r), 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 4 and 5 that $P^m_s > P^m_s$ for any series compensation level (%S) because of the loss in the line. From Figure 4 it can be noted that when %S = 0 the value of P^m_s 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 P^m_s decreases when K > 0.45. A similar pattern for p^m_r be observed from
Figure 5 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 4, when %S = 15 then P^m_s 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^m_s 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).

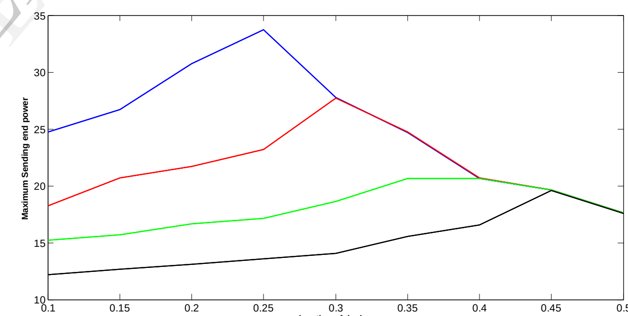
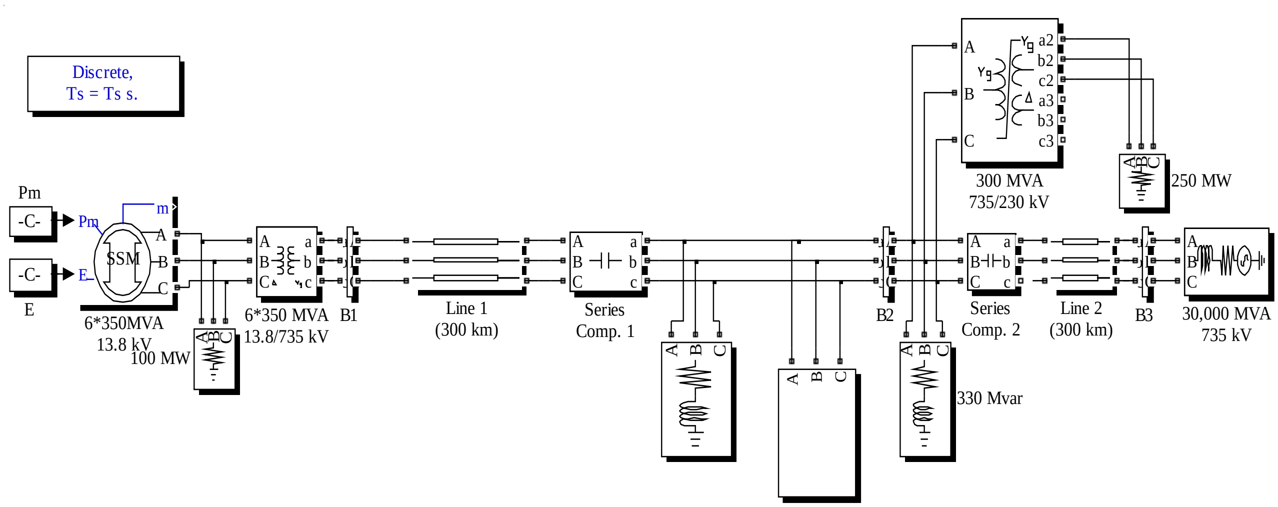


Fig 4. Variation in maximum sending end power for different levels of %S



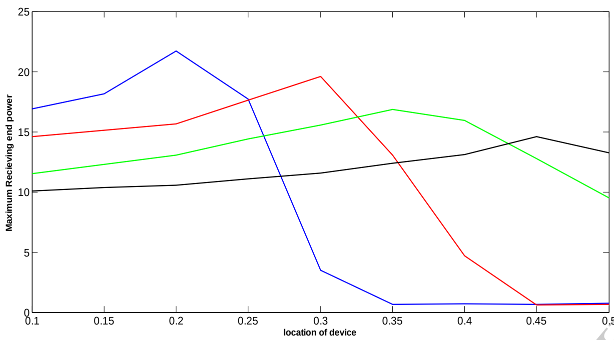


Fig 5.Variation in maximum receiving end power for different levels of %S

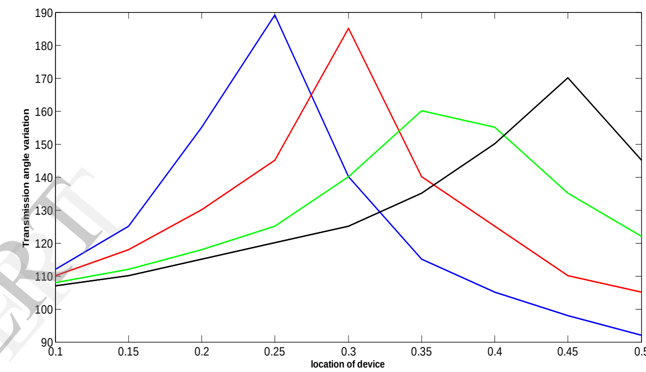


Fig 6. Variation in transmission angle at the maximum SE power for different levels of %S.

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 5 for different series compensation levels. In Figure 6, it can be observed that in the absence of series compensation (%S = 0) the angle at the maximum SE power increases from 95.8^o at K = 0 to its maximum value 171.1^o 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 185^o 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 7 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.

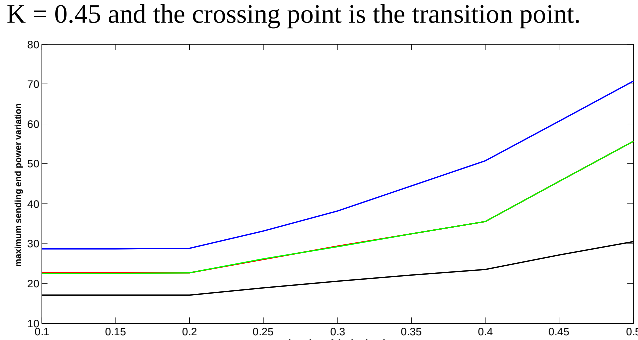


Figure 7. Variation of the maximum RE power against the value of K for different series compensation levels (%S).

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. 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.

4. Conclusion

This paper presents the effect of series compensation of transmission lines 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 the proposed method. 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 series and shunt compensations controllers in enhancing power system stability has been examined.

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