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Placement of FACTS Devices in a Series Compensated Long Transmission Line

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ABSTRACT

Static VAR Compensator (SVC)and Static Synchronous Compensator (STATCOM) are important devices in FACTS family, and is widely recognized as an effective and economical means to solve the power system stability problem. SVC and STATCOM are used as shunt in transmission system. In the present work a series compensated Distributed transmission line (345KV, 450km, 50Hz) with a shunt FACTS devices SVC and STATCOM is considered to the optimal location of the shunt FACTS devices to get the highest possible benefits of maximum power transfer and system stability. 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. All the simulations for the above work have been carried out using MATLAB /SIMULINK software.

Keywords:*optimal placement, SVC, STATCOM,, degree of series compensation, long transmission line etc,*.

I. INTRODUCTION

The FACTS controllers offer a great opportunity to regulate the transmission of alternating current (AC), increasing or diminishing the power flow in specific lines and responding almost instantaneously to the stability problems. The potential of this technology is based on the possibility of controlling the route of the power flow and the ability of connecting networks that are not adequately interconnected, giving the possibility of trading energy between distant agents. It is meant to enhance controllability and increase power transfer capability. It is generally power electronics baseddevice. The FACTS devices can be divided in three groups, dependent on their switching technology: mechanically switched (such as phase shifting transformers), thyristor switched or fast switched, using IGBTs. While some types of FACTS, such as the phase shifting transformer (PST) and the static VAR compensator (SVC) are already well known and used in power systems, new developments in power electronics and control have extended the application range of FACTS. Furthermore, intermittent renewable energy sources and increasing international power flows provide new applications for FACTS. The additional flexibility and controllability of FACTS allow to mitigate the problems associated with the unreliable of supply issues of renewable. SVCs and STATCOM devices are well suited to provide ancillary services (such as voltage control) to the grid and fault rid through capabilities which standard wind farms cannot provide Furthermore, FACTS reduce oscillations in the grid, which is especially interesting when dealing with the stochastic behavior of renewable.

II. MODELING OF THE SVC

The SVC provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control through its utilization of high-speed thyristor switching/controlled reactive devices. An SVC is typically made up of the following major components:

1. Coupling transformer
2. Thyristor valves
3. Reactors
4. Capacitors (often tuned for harmonic filtering)

In general, the two thyristor valve controlled/switched concepts used with SVCs are the thyristor-controlled reactor (TCR) and the thyristor-switched capacitor (TSC). The TSC provides a “stepped” response and the TCR provides a “smooth” or continuously variable susceptance.Fig. 1 illustrates a TCR/FC including the operating process concept. The control objective of SVC is to maintain the desired voltage at a high voltage bus. In steady- state, the SVC will provide some steady- state control of the voltage to maintain it the highest voltage bus at the pre-defined level. If the voltage bus begins fall below its setpoint range, the SVC will inject reactive power (Q_{net}) into the system (within its control limits), thereby increasing the bus voltage back to its desired voltage level. If bus voltage increases, the SVC will inject less (or TCR will absorb more) reactive power (within its control limits), and the result will be to achieve the desired bus voltage. From Fig. 1, $+Q_{cap}$ is a fixed value, therefore the magnitudes of reactive powerinjectedinto the system, Q_{net} is controlled by the magnitude of $-Q_{ind}$ reactivepower absorbed by the TCR

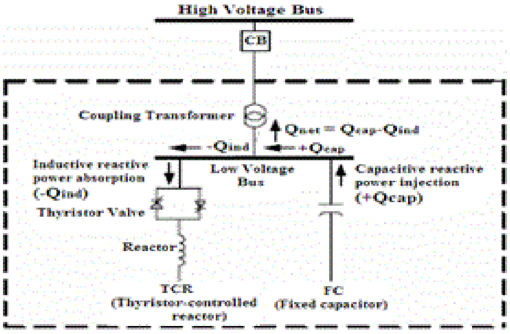

Fig 1.Block diagram of a TCR-FC SVC

A. Dynamic Response of the SVC

When the SVC is operating in voltage regulation mode, itsresponse speed to a change of system voltage depends on the voltage regulator gains (proportional gain K_P and integral gain K_i, the droop reactance X_S, and the system strength (shortcircuit level). For an integral-type voltage regulator ($K_P = 0$), if the voltage measurement time constant Tm and the averagetime delay T_d due to valve firing are neglected, the closed-loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:

$$T_C = \frac{1}{K_i.(X_S+X_n)} (1)$$

Where

T_C = Closed loop time constant

K_i = proportional gain of the voltageregulator(p.u./P_{base})

X_S = Slope reactance (p.u. /P_{base})

B. Description of Static VAR Compensator

The static VAR compensator (SVC) is a shunt device of theflexible AC transmission systems (FACTS) family usingpower electronics to control power flow and improve transientstability on power grids.

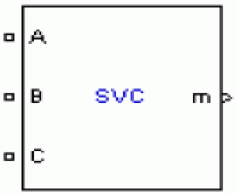

Fig 2.SVC Block

The SVC regulates voltage at itsterminals bycontrolling the amount of reactive power injectedinto or absorbed from the power system.Each capacitor bank is switched on and off by three thyristorswitches (Thyristor Switched Capacitor or TSC). Reactors areeither switched on-off (Thyristor Switched Reactor or TSR) orphase-controlled (Thyristor Controlled Reactor or TCR).

C. Single-line Diagram of an SVC and Its Control System

The control system consists of,

-A measurement system measuring the positive-sequencevoltage to be controlled. A Fourier-based measurement systemusing a one-cycle running average is used.

-A voltage regulator that uses the voltage error (differencebetween the measured voltage V_m and the reference voltage V_{ref}) to determine the SVC susceptance B needed to keep thesystem voltage constant.

-A distribution unit that determines the TSCs (andeventuallyTSRs) that must be switched in and out, and computes thefiring angle M of TCRs.

-A synchronizing system using a phase-locked loop (PLL)synchronized on the secondary voltages and a pulse generatorthat send appropriate pulses to the thyristors. This is shown inFig. 3.

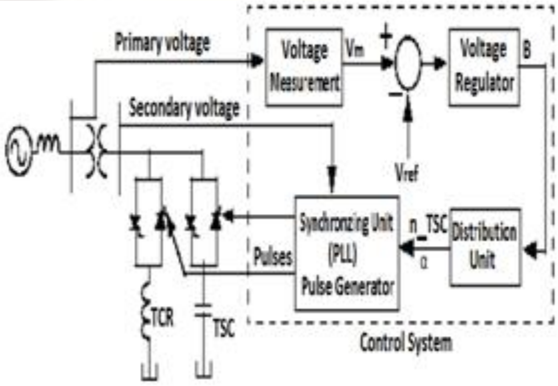

Fig 3.The control system of SVC

D. SVC V-I Characteristic

The SVC can be operated in two different modes: In voltageregulation mode and in VAR control mode (the SVCsusceptance is kept constant) when the SVC is operated involtage regulation mode, it implements the following V-Icharacteristic. As long as the SVC susceptance B stays withinthe maximum and minimum susceptance values imposed bythe total reactive power of capacitor banks (B_{Cmax}) and reactorbanks (B_{lmax}) the voltage is regulated at the reference voltageV_{ref}. However, a voltage droop is normally used (usuallybetween 1% and 4% at maximum reactive power output), andthe V-I characteristic has the slope indicated in the Figure.4.The V-I characteristic is described by the following three equations:

SVC is in regulation range$(-B_{Cmax} < B < B_{lmax})$

$V = \frac{I}{B_{Cmax}} (2)$

$V = V_{ref} + X_s.I (3)$

SVC is fully capacitive$(B = B_{Cmax})$

$V = \frac{I}{B_{lmax}} (4)$

SVC is fully capacitive$(B = B_{lmax})$

Where,

V = Positive sequence voltage (p.u.)

I = Reactive current (p.u./P_{base}) (I > 0 indicates an inductivecurrent)

X_s = Slope or droop reactance (p.u. /P_{base})

B_{Cmax} = Maximum capacitive susceptance (p.u. $/P_{base}$) with allTSCs in service, no TSR or TCR
B_{lmax} = Maximum inductive susceptance (p.u. $/P_{base}$) with allTSRs in service or TCRs at full conduction, noTSC
P_{base} = Three-phase base power

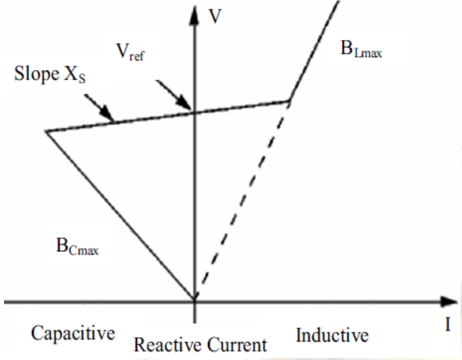

Fig 4.The V-I Characteristics Curve of SVC

III. MODELING OF THE STATCOM

A. Configuration

STATCOM is one of the important shunt connected Flexible AC Transmission Systems (FACTS) controllers to control power flow and make bettertransient stability. The basic structure of STATCOM in schematic diagram is shown in Figure 6. It regulates voltage at its terminal by changing the amount of reactive power in or out from the power system. When system voltage is low, the STATCOM inject reactive power. When system voltage is high, it absorbs reactive power.

B.Phase angle control

In this case the quantity controlled is the phase angle δ. The modulation index "m" is kept constant and the fundamental voltage component of the STATCOM is controlled by changing the DC link voltage. By further charging of the DC link capacitor, the DC voltage will be increased, which in turn increases the reactive power delivered or the reactive power absorbed by the STATCOM. On the other hand, by discharging the DC link capacitor, the reactive power delivered is decreased in capacitive operation mode or the reactive power absorbed by the STATCOM in an inductive power mode increases.For both capacitive and inductive operations in steady-state, the STATCOM voltage lags behind AC line voltage ($\delta > 0$).

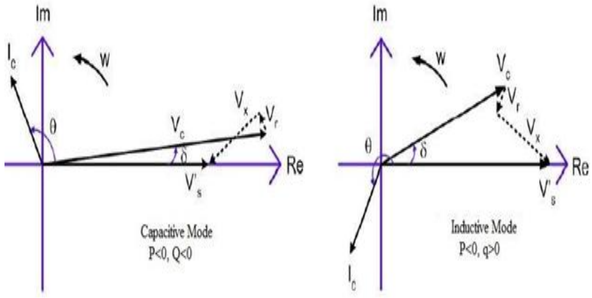

Fig 5.Phase angle control of Capacitive and Inductive mode

By making phase angle δ negative, power can be extracted from DC link. If the STATCOM becomes lesser than the extracted power, Pc in becomes negative and STATCOM starts to deliver active power to the source. During this transient state operation, V_d gradually decreases.

The phasor diagrams which illustrating power flow between the DC link in transient state and the ac supply is shown in above Figure 5.

For a phase angle control system, the open loop response time is determined by the DC link capacitor and the input filter inductance. The inductance is applied to filter out converter harmonics and by using higher values of inductance; the STATCOM current harmonics is minimized.

C. Operating Principle of the STATCOM

The operating principle of STATCOM isexplained in the figure.1 showing the active andreactive power transfer between a power systemand a VSC. In this figure, V1 denotes the powersystem voltage to be controlled and V2 is thevoltage produced by the VSC.

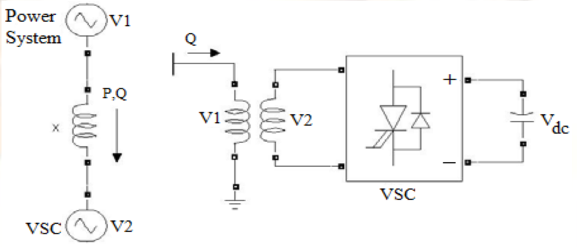

Fig 6.Schematic representation of STATCOM

During steady state working condition, thevoltage V2 produced by the VSC is in phase withV1 (i.e.=0), so thatonly reactive power is flowing(Active power P=0). If the magnitude of voltage V2produced by VSC is less than the magnitude ofpower system voltage V1, reactive power Q isflowing from power system to VSC (STATCOM isabsorbing reactive power mode). If V2 is greaterthan V1, Q is flowing from VSC to power system(STATCOM is producing reactive power mode). IfV2 is equal to V1 the reactive power exchange iszero. The amount of reactive power is given by

$$Q = \frac{V_1(V_1 - V_2)}{X} \quad (5)$$

D. STATCOM V-I characteristic

Modes of the STATCOM operation:

1) Voltage regulation mode
2) VAR control mode

When the STATCOM is worked in voltageregulation mode, it implements the V-Icharacteristic as shown in Fig. 7.The V-Icharacteristic is depicted by the following equation:

$$V = V_{ref} + X_s . I$$

Where

V= Positive sequence voltage (p.u)
I = Reactive current (p.u. /P_{nom})
(I > 0 indicates an inductive current and I< 0indicates capacitive current)
X_s = Slope (p.u. /P_{nom} : usually between 1% and 5%)
P_{nom} =Converter rating in MVA

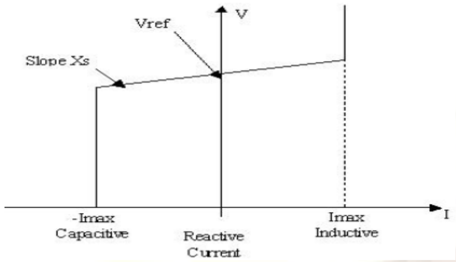

Fig 7.V-I characteristics of STATCOM

IV. TRANSMISSION LINE MODEL

In this paper, the transmission line is modeled by a two port, four terminal networks asShown in Figure 3.Transmission lines are operated with a balanced three phase load; the analysis can therefore proceed on a per phase basis. A transmission line on a per phase basis can be regarded as a two port network, where in the sending end voltage V_S and current I_S are related to thereceiving end voltage V_r and current I_r through ABCD constants as

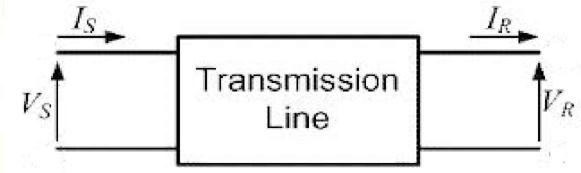

Fig 8.Two port model of a transmission line.

$V_S = AV_r + BI_r$(6)
$I_S = CV_r + DI_r$(7)

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(γl) B=Z_C sinh(γl)
C = sinh(γl)(8)
Where,

$Z_C = \sqrt{z/y}\,\gamma = \sqrt{zy}$

Z_C =Characteristic impedance of the line
γ =Propagation constant of the line
z=series impedance/unit length/phase
y =shunt admittance/ unit length/phase to neutral
l=transmission line length
α=attenuation constant
β=phase constant

A. Power flow through a transmission line for a actual line model

The principle of power flow through a transmission line is illustrated through a single transmission line (2-node/2-bus system).Let us consider receiving-end voltage as a reference phasor ($|V_S|\llcorner 0$) and let the sending end voltage lead it by an angle δ is known as the torque angle.

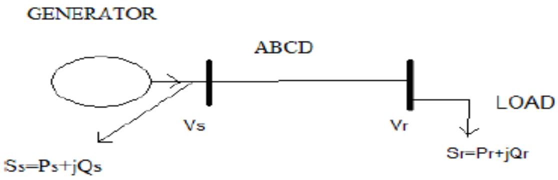

Fig 9.A Two bus system.

The complex power leaving the RE and entering the SE of the transmission line can be expressed as

$S_r = P_r + Q_r = V_r I_r*$ (9)
$S_s = P_s + Q_s = V_s I_s$(10)

The real and reactive power flows at the sending-end and receiving-end of the line can be written as

$P_S = C_1\cos(\beta - \alpha) - C_2\cos(\beta - \delta)$(11)
$Q_S = C_1\sin(\beta - \alpha) - C_2\cos(\beta - \delta)$(12)
$P_S = C_2\cos(\beta - \delta) - C_3\cos(\beta - \alpha)$ (13)
$P_S = C_2\sin(\beta - \delta) - C_3\cos(\beta - \delta)$(14)
Where,
$C_1 = AV_S{}^2/B$
$C_2 = V_s V_r/B$
$C_3 = AV_r{}^2/B$
$A = A\llcorner\alpha,\ B = B\llcorner\beta$
$V_r = V_r\llcorner 0, V_s = V_s\llcorner\delta$

It is clear from Eq. (15) that the RE power reaches the maximum value when the angle δ becomes β. However, the SE power P_S of Eq. (13) becomes maximum at δ = (Π− β). 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 × 106 S/km, respectively, at 50 Hz. The parameters are obtained using the MATLAB /SIMULINK software. The results of the line are presented in p.u. on a 100 MVA, 345 kV base [3].

V. 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 center and a shunt FACTS device at point ‘m’ as shown in Figure 10. Parameter k is used to show the fraction of the line length at which the FACTS device is placed. The shunt FACTS device are SVC and STATCOM and is usually connected to the through a step-down transformer. 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 10) with its own ABCD constants considering the actual line model

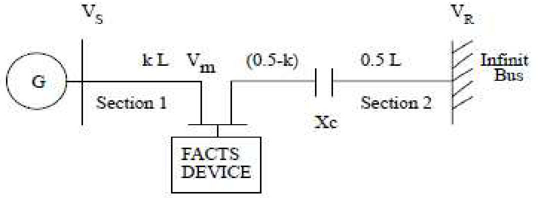

Fig 10.Series compensated transmission line with a shunt FACTS device [3].

VI. RESULTS AND DISCUSSIONS

CASE STUDY

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

$$P = P_m \sin\delta (15)$$

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. (11) and (13) instead of Eq. (15) 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) ($P_{R\,1}$=P_{S2}) is included 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 11-13 show the variation in maximum RE power ($P_R{}^m$), maximum sending end power ($P_S{}^m$), 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 11 and 12 that $P_S{}^m$>$P_R{}^m$ for any series compensation level (%S) because of the loss in the line. From Figure 11 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 11 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 10, 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).

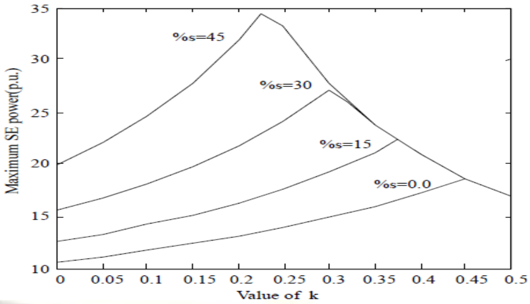

Fig 11.Variation in maximum SE power for diff. value of %S.

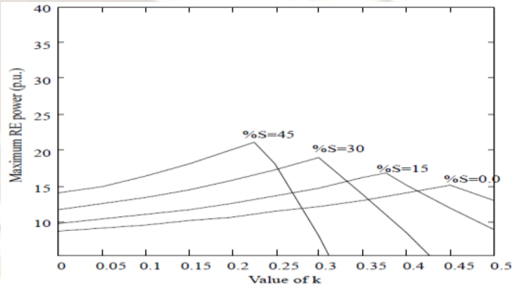

Fig 12.Variation in maximum RE power for diff. value of %S.

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 12 for different series compensation levels. In Figure 13, it can be observed that in the absence of series compensation (%S = 0) the angle at the maximum SE power increases from 95.8^0 at K = 0 to its maximum value 171.1^{0}at K = 0.45. When %S = 15 then δ^m increases when K is increased and reaches its maximum value 180.5^{0}at K = 0.375. When %S = 30 then δ^m increases when K is increased and reaches its maximum value 180.5^{0}at K = 0.3 and for %S= 45 it is 188^0 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.

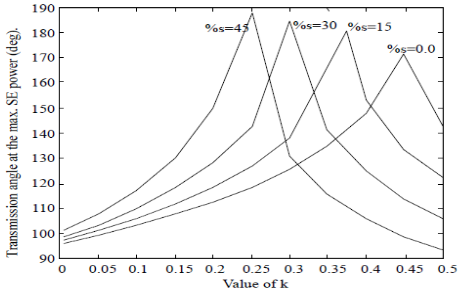

Fig 13.Variation in transmission angle at the max.SE power for diff. value of %S.

Figure 8 shows the variation of the maximum RE power of section 1 ($P_{R1}{}^m$) and maximum SE power ofsection 2 ($P_{S2}{}^{m}$) against the value of K for different series compensation levels (%S). It can be seen in Figure8 that for an uncompensated line then maximum power curves cross at K = 0.45 and the crossing point isthe transition point.

Thus, to get the highest benefit in terms of maximum It means that when series compensation level (%S) isincreased 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.

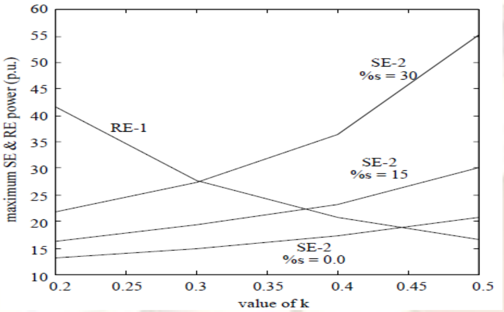

Fig 14.Variation in the maximum RE power of section-1 and SE power of section-2 against k for diff. value of %S.

VII. 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. 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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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. 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.

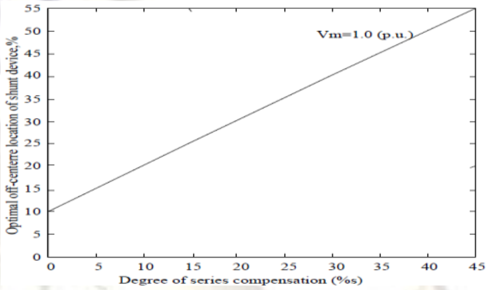

Fig 15.Variation in the optimal off-center location of shunt FACTS device against degree of compensation of line (%S).

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