

# Positioning of SVC and STATCOM in a Long Transmission Line

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**Abstract**—Shunt Flexible AC Transmission System (FACTS) device such as SVC and STATCOM, when placed at the midpoint of a long transmission line, play an important role in controlling the reactive power flow to the power network and hence both the system voltage fluctuations and transient stability. The validity of the mid-point location of these FACTS devices is investigated, when the actual model of the line is considered. This paper deals with the effects of considering the actual line model on the power transfer capability and stability when the shunt FACTS device is connected to the line. An attempt was made to determine the optimal positioning for placing the FACTS device in case of a 5-bus system to evaluate voltage stability and power flow angle characteristics for both the simplified and actual model.

**Index Terms**—SVC, STATCOM, Transient stability, Voltage fluctuations

## I. INTRODUCTION

Recent development of power electronics introduces the use of FACTS devices in power systems. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to improve the transient stability of a system. Reactive power compensation is an important issue in electrical power systems and shunt FACTS devices play an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and transient stability.

The flexible AC transmission system (FACTS) are now recognized as a viable solution for controlling transmission voltage, power flow, dynamic response, etc. and represent a new era for transmission systems. It uses high-current power electronic devices to control the voltage, power flow, etc. of a transmission system. FACTS devices are very effective and capable of increasing the power transfer capability of a line, if the thermal limit permits, while maintaining the same degree of stability. SVC and STATCOM are members of FACTS family that are connected in shunt with the system. Even though the primary purpose of shunt FACTS devices is to support bus voltage by injecting (or absorbing) reactive power, they are also capable of improving the transient stability by increasing (decreasing) the power transfer capability when the machine angle increases (decreases), which is achieved

by operating the shunt FACTS devices in capacitive (inductive) mode.

Previous works on the topic prove that shunt FACTS devices give maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line. The proof of maximum increase in power transfer capability is based on the simplified model of the line neglecting line resistance and capacitance. However, for long transmission lines, when the actual model of the line is considered, the results may deviate significantly from those found for the simplified model.

The primary objective of our project is to find the maximum power and the corresponding location of the shunt FACTS devices when the actual line model is considered. Based on the simplified line model it has been proved that the centre or midpoint of a transmission line is the optimal location for shunt FACTS devices. When the actual model of the line is considered, it is found that the FACTS device needs to be placed slightly off-centre to get the highest possible benefit. To facilitate the same the objectives have been listed below as:-

1. To find the maximum power and the corresponding location of the shunt FACTS devices when the actual line model is considered.
2. To compare the optimal location obtained for both the simplified and actual line model of a 345kV, 450km line.
3. To compare the power-angle characteristics and stability for both simplified and actual line model.
4. To find the optimal location of shunt FACTS device when a 5-bus system is considered.

Haque, M.H. [1] investigated the effects of the actual line model on the optimal location of shunt FACTS devices to get the highest possible benefit. IEEE Task Force [3] presents the results of Task Force 3 of the IEEE's FACTS Working Group of the DC and FACTS Subcommittee which had the assignment to establish appropriate definitions of FACTS-related terminology. FACTS are an evolving technology-based solution envisioned to help the utility industry to deal with changes in the power delivery. Kimbark, E.W. [8] has dealt with raising the stability limit of a power system examined with respect to their employment at or near the electrical center of a two-machine system. New concept of current gain, voltage gain are defined and illustrated. Shunt devices are most effective when connected at the

electrical centre of a transmission system and their effectiveness falls off rapidly when a change in the transmission system throws them off-centre. Kazerani, B.T. [10] studied how FACTS devices derive maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line. The power transfer capacity is increased to twice that of the uncompensated line. The mid-point sitting is also most effective in reactive power control. The transmission line must be operating below the thermal limit and the transient stability limit. Tan, Y.L [11] suggested a novel method for the analysis of the effectiveness of an SVC and a STATCOM of the same KVar rating for first-swing stability enhancement is presented and the concept is demonstrated with a numerical example. The analysis shows that the STATCOM is superior to the SVC for first-swing stability enhancement. Siddhartha Panda, Ramnarayan N. Patel[11] investigated about the Shunt Flexible AC Transmission System (FACTS) devices, when placed at the mid-point of a long transmission line, play an important role in controlling the reactive power flow to the power network and hence both the system voltage fluctuations and transient stability. This paper deals with the location of a shunt FACTS device to improve transient stability in a long transmission line with predefined direction of real power flow. It has been observed that the FACTS devices, when placed slightly off-centre towards sending-end, give better performance in improving transient stability and the location.

II. TRANSMISSION LINE MODEL

In this paper, the transmission line is modeled by a two-port, four terminal networks as shown.



Figure 1. Two port four terminal model of a transmission line.

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, wherein the sending end voltage  $V_s$  and current  $I_s$  are related to the receiving end voltage  $V_r$  and current  $I_r$  through ABCD constants as

$$V_s = AV_r + BI_r \tag{1}$$

$$I_s = CV_r + DI_r \tag{2}$$

The ABCD constants of a line of length  $l$ , having a series impedance of  $z \Omega/\text{km}$  and shunt admittance of  $y \text{ S}/\text{km}$  are given by

$$A=D=\cosh(\gamma l) \quad B=Z_c \sinh(\gamma l)$$

$$C=\sinh(\gamma l)$$

Where,

$$Z_c = \sqrt{z/y} \quad \gamma = \sqrt{zy}$$

- $Z_c$ =characteristic impedance of the line
- $\gamma$ =propagation constant of the line
- $z$ =series impedance/unit length/phase
- $y$ =shunt admittance/unit length/phase to neutral
- $l$ =transmission line length
- $\alpha$ =attenuation constant
- $\beta$ =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 ( $|V_s| \angle 0$ ) and let the sending end voltage lead it

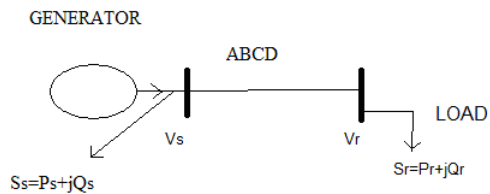


Figure 2 A Two bus system.

by an angle  $\delta$  is known as the torque angle.

The complex power leaving the receiving end and entering the sending-end of the transmission line can be expressed as

$$S_r = P_r + jQ_r = V_r I_r^* \tag{3}$$

$$S_s = P_s + jQ_s = V_s I_s \tag{4}$$

Receiving and sending end currents can be expressed in terms of receiving and sending end voltages.

$$I_r = \left| \frac{1}{B} \right| |V_s| \angle(\delta - \beta) - \left| \frac{A}{B} \right| |V_r| \angle(\alpha - \beta) \tag{5}$$

$$I_s = \left| \frac{D}{B} \right| |V_s| \angle(\alpha + \delta - \beta) - \left| \frac{1}{B} \right| |V_r| \angle -\beta \tag{6}$$

We can write the real and reactive powers at the receiving-end and the sending end as

$$P_s = C_1 \cos(\beta - \alpha) - C_2 \cos(\beta + \delta) \tag{7}$$

$$P_r = C_2 \cos(\beta - \delta) - C_3 \cos(\beta - \alpha) \tag{8}$$

$$Q_s = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta + \delta) \tag{9}$$

$$Q_r = C_2 \sin(\beta - \delta) - C_3 \sin(\beta + \delta) \tag{10}$$

III POWER FLOW IN A TRANSMISSION LINE WITH FACTS DEVICE

A Shunt FACTS devices in a power system

Consider that the line is transferring power from a large generating station to an infinite bus and equipped with a shunt FACTS device at point m. a parameter  $k$  is

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used to show the fraction of line length at which the FACTS device is placed.

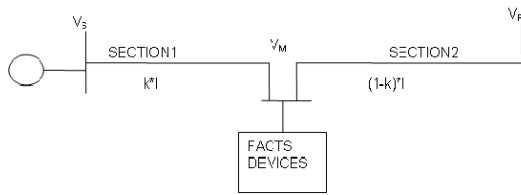


Figure 3 Transmission Line with the FACTS device.

1) For a Simplified Model

The power transfer through the line for given values of SE and RE voltage magnitude is given by eq. (15) and can be written as

$$P = P_m \sin \delta$$

Here the maximum power  $P_m$  is  $\frac{V_S V_R}{X}$

When a shunt FACTS device is connected to the line both  $P_m$  and  $\delta_m$  are increased and their values depend on the k factor. The power transfer through the line is then given by

$$P = \frac{V_S V_m}{k X_L} \sin \delta_S = \frac{V_R V_m}{(1-k) X_L} \sin \delta_R \quad (11)$$

Here the SE power is equal to the RE power because the line is lossless.

$$P = \frac{P_0 \sin \delta_S}{k} = \frac{P_0 \sin \delta_R}{1-k} \quad (12)$$

2) For Actual Line Model

The ABCD constants of a line of length l, having a series impedance of z ohms/km and shunt admittance of y S/km with FACTS devices the active and reactive power flows at the SE and RE of the line can be shown in the table

Table1 SE and RE real and reactive power with the shunt FACTS Devices

Section1	Section2
$P_s = C_1 \cos(\beta - \alpha) - C_2 \cos(\beta + \delta_s)$	$P_s = C_1 \cos(\beta - \alpha) - C_2 \cos(\beta + \delta_R)$
$Q_s = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta + \delta_s)$	$Q_s = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta + \delta_R)$
$P_r = C_2 \cos(\beta - \delta_s) - C_3 \cos(\beta - \alpha)$	$P_r = C_2 \cos(\beta - \delta_R) - C_3 \cos(\beta - \alpha)$
$Q_r = C_2 \sin(\beta - \delta_s) - C_3 \sin(\beta - \alpha)$	$Q_r = C_2 \sin(\beta - \delta_R) - C_3 \sin(\beta - \alpha)$

IV RESULTS AND DISCUSSIONS

A CASE STUDY -1

A 345KV, single circuit transmission line of length 450km is considered. The series and shunt admittance of the line is  $z = (.02986 + j.2849)$  ohms/km and  $y = (j3.989 * 10^{-6})$  S/km respectively, at 50Hz. The results of the line is presented in p.u. on a 100MVA, 345KV base. Here  $V_S = V_R = V_m = 1.0$  p.u. is used.

The various parameters of this line are calculated and are presented as follows:

Table 2 Values of various parameters of the line

VARIABLE	VALUES
A	0.8871 + 0.0116i
B	0.0104 + 0.1037i
C	-0.0084 + 2.0555i
D	0.8871 + 0.0116i
A	0.013
$\beta$	1.4705
$\gamma$	0.0001 + 0.0011i
$\delta$	0
$P_s$	0.0022
$P_r$	-0.0022
$Q_s$	-1.0892
$Q_r$	1.0892

A MATLAB program is written to determine the various characteristics of the system. In all cases  $V_S = V_R = V_m = 1.0$  p.u is used. Figure 3 show the maximum power  $P_m$  and the corresponding angle  $\delta_m$  are determined for various values of k and a graph is plotted.

From the graph it is seen that it is observed that the maximum SE power is equal to the max RE power because the line is lossless. The maximum power

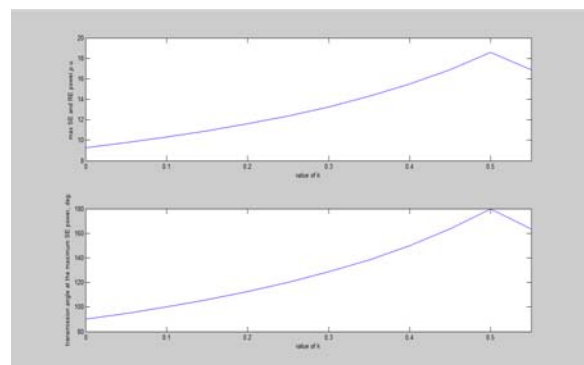


Figure 4 Variation of SE and RE power and transmission angle for the simplified Model

increases from 9.3 p.u. (for k=0) to double the value i.e. 18.6 p.u. (for k=0.5) and then decreases, Angle  $\delta_m$  at max. SE power increases from 90° (at k=0) to 180° (at k=0.5) and then decreases.

It is clear from eq. (4) that the RE power  $P_R$  reaches the maximum value when the angle  $\delta$  becomes  $\beta$ . However, the SE power  $P_S$  of eq. (3) becomes maximum at  $\delta = (\pi - \beta)$ . The maximum power flow for actual line model is given by equations

$$P_S = C_1 \cos(\beta - \alpha) + C_2 \quad (13)$$

$$P_R = C_2 - C_3 \cos(\beta - \alpha) \quad (14)$$

Using the above equations a graph is plotted for the variation of maximum sending end and receiving end power with different values of k.

If the maximum receiving end power of section 1 is greater than the maximum sending end power of section 2 then the max. SE power of section 2 is plotted and vice-

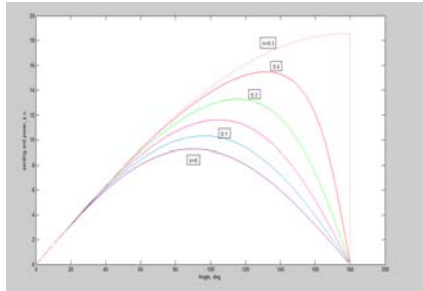


Figure 5 Power Angle characteristics for the simplified model

versa.

The maximum transmission angle corresponding to the maximum SE power is also plotted for different values of k.

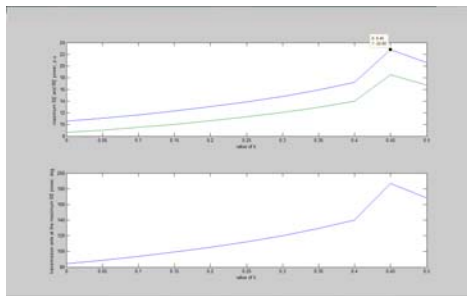


Figure 6 Variation of SE and RE power and transmission angle for the actual line model

From eq. (12), the value of transmission angle for a particular value of k can be given by

$$\delta = \delta_S + \delta_R$$

$$\delta = \sin^{-1} k \frac{P}{P_0} + \sin^{-1} (1-k) \frac{P}{P_0} \quad (15)$$

.As the value of  $\delta_S$  and  $\delta_R$  increases the power through the line first increases and then decreases having max. Value at  $\delta_R = \delta_S = 90^\circ$

Here, the maximum power in the long section is lesser than the max power in the short section and hence the power in the whole line is limited and equal to the power in the long section.

Hence the sum of the value of  $\delta_S$  corresponding to the maximum value of P in the long section and  $\delta_R$  at which maximum power occurs gives the maximum  $\delta$  for the whole line.

The inverse of the sine term are multiple valued, each having two values in the range of  $\delta$  from 0 to  $\pi$ .

The only way in which  $\delta$  can increase and be a continuous function of P is to go up one branch and down

the other of the lower sinusoid and at the same time go up and down the same (left-hand) branch of the taller sinusoid.

The instantaneous ‘jump’ in  $\delta$  is not possible because both the terminal machines have inertia.

Thus, a P- $\delta$  graph is plotted for various values of k.

papers published in translated journals, first give the English citation, then the original foreign-language citation [6].

It can be noticed that the maximum power increases as the value of k is increased.

However, an unusual pattern of the P- $\delta$  is observed for k=0.5. For k $\leq$ 0.4, all the P- $\delta$  curves approach 191.8 $^\circ$ (at zero power). But for k=0.5 the P- $\delta$  curve is shifted towards the left after reaching the maximum power and approaches 167.1 $^\circ$ (at zero power).The above change in pattern significantly affects the stability of the system. Even though the max. Power for k=0.5 is higher than that for k=0.4, the system is less stable for k=0.5.This happens because of the smaller decelerating area caused by the shift of the P- $\delta$  curve towards the left. The reason for the shift of P- $\delta$  curve is further investigated.

The P- $\delta$  curve of the half-length of the line is plotted.

The optimal location of the shunt FACTS device depends on the line resistance or loss and hence the R/X ratio of the line.

It is observed that the optimal off-centre location increases linearly as the value of R/X ratio of the line is increased.

The slope of the line is about 0.5% for Vm=1.0 p.u. The line capacitance is found to have a very insignificant effect on all the results. However it slightly affects the amount of reactive power supplied by the shunt FACTS device.

**B. CASE STUDY -2**

Consider the five bus system. All seven lines are characterized by a series impedance of 0.211 +j0.851  $\Omega$ /mi and a shunt admittance of 5.21 $\mu$  /mi

The lines are rated at 138 kV and have the following lengths:

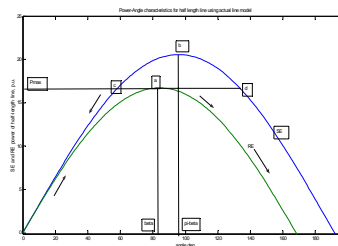


Figure 7 Power Angle characteristics for the actual line model

L1:70.4 miles; L2:53.1miles; L3:40.8miles; L4:71.9 miles; L5:62.8 miles; L6:30.6 miles; L7:98.4 miles  
Base values are 100 MVA, 230kV

Line having the minimum P<sup>cr</sup> value is called the weakest bus. From above data it can be concluded that line, L7, between bus 4 & 5 is the weakest bus. The compensation is provided to the weakest bus, so in this case study we need to install the FACTS devices in the

line L7. Thus the a FACTS device is placed in Line 7, between bus 4 and bus 5. When the FACTS device is placed in Line 7, the line gets divided into two sections i.e. section 1 and section 2. The optimal location for this FACTS device is determined by plotting the following graphs.

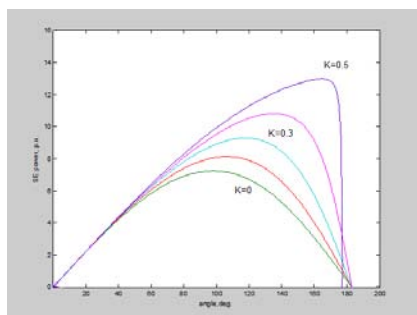


Figure 8 Power angle characteristics for the actual line model in the 5 bus system

It is seen that maximum SE and RE power is obtained at  $k=0.49$  which is slightly off-centre. Also the

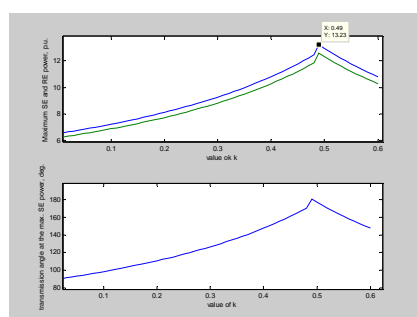


Figure 9 Variation of RE, SE power and transmission angle for the actual line in line 7

transmission angle corresponding to the max. SE power is maximum at  $k=0.49$  and then decreases for values  $k > 0.49$ .

The maximum RE power of section 1 is equal to the max. SE power of section 2 at  $k=0.486$  and thus it is the optimal location.

Thus the FACTS device needs to be placed at a distance of 47.8 miles from bus 4 on line 7 in order to achieve maximum power transfer through the line.

### CONCLUSIONS

It has been found that the shunt FACTS device needs to be placed slightly off-centre to get highest possible benefit when the power flows in the particular direction. The optimal location from the centre point depends on the line resistance and increase almost linearly as the R/X ratio of the line is increased.

The results found in this paper would be useful in selecting the best location for various shunt FACTS devices to get the highest possible benefit when the pattern of power flow of the line is known. It is also found that some of the results obtained or conclusions made for the simplified line model are not valid for the actual line model, especially when the FACTS device is placed at the midpoint.

In the future, FACTS devices could be installed on a wide scale by electrical utilities in an attempt to control the power flows through their networks. It is also recognized as a viable solution for controlling transmission voltage, power flow, and dynamic response.

### ACKNOWLEDGMENT

The authors wish to thank management of VIT for their constant encouragement in promoting this research work.

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