LOAD FLOW ANALYSIS OF TRANSMISSION NETWORK WITH SERIES COMPENSATION

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Abstract

The increase in electrical energy demand has presented higher requirements from the power industry during past two decades. In recent years, the highly increasing cost of building new transmission lines, compounded by the difficulty to obtain new transmission corridors, has led to a search for increasing the transmission capacity of existing lines. Use of series capacitors for compensating part of the inductive reactance of long transmission lines increases the power transmission capacity as well as improves the system stability. Transmission line compensation implies a modification in the electric characteristic of the transmission line with the objective of increase power transfer capability. The series compensator is primarily applied to solve load flow problems which may be related to length of line or structure of transmission network. This paper presents an analysis of the location of series capacitor, effect of series line compensation level on the line voltage profile, transferred power and transmission losses. Also it gives information about problem formulation for load flow analysis. For this purpose simple three bus model has been developed in MATLAB/SIMULINK. It gives basic mechanism of series compensation also highlight its benefits for power system.

Keywords: *Line Reactance, Series Compensation, Degree of Compensation, Capacitive Reactance, Transmission Efficiency*

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1. INTRODUCTION

In AC power transmission system, compensation is the management of reactive power to improve the reliability of power system. To improve the system reliability, stability, efficiency, cost effectiveness by means of compensation there are mainly two methods,

1. Shunt compensation: The shunt compensator is functionally a controlled reactive current source which is connected in parallel with the transmission line to control its voltage.
2. Series compensation: The series compensator is functionally a controlled voltage source which is connected in series with the transmission line to control its current

As per Rolf Gruenbaum, Dr. G. Thomas Bellamhe, in transmission system, due to the transmission line reactance, there are limitations on power transmit ability of line so that it leads towards building of new transmission line which is costly affair. Series capacitive compensation is used to increase power transmission capability by canceling the line reactance [1], [2]. Ullasn Eminoglu reported that, voltage regulation becomes an important and sometimes critical issue in the presence of load, which varies the demands for reactive power [3]. As per Rolf Gruenbaum, Belur S. location of the compensator is also an important aspect [4], [5]. Adebayo reported that series capacitor compensation provides additional options for load flow control and voltage stability of power system [6]. Compensation means the modification of electrical characteristics of a transmission line in order to increase its power transmission capacity, to satisfy the fundamental requirements for transmission. Compensation system ideally performs following functions:

1. It helps to improve voltage profile at all levels of power transmission.
2. It improves stability by increasing the maximum transmittable power.
3. It provides an economical means for meeting the reactive power requirements of the transmission system.

The paper is organized in different sections. First section gives introduction about series capacitor compensation and load flow power. The second section describes operating principle of series compensation and its functional capabilities. The third section deals with a selection of series capacitor for series compensation and its location. Fourth section gives the information about power system selection and problem formulation for load flow analysis. Fifth section deals with MATLAB/SIMULINK modeling and results.

2. BASIC MECHANISM

Series capacitive compensation was introduced to cancel a portion of the reactive line impedance and thereby increase the transmittable power. The variable series compensation is highly effective in both controlling power flow in the line and improving stability. The usefulness of the concept can be illustrated by means of example in Fig.1

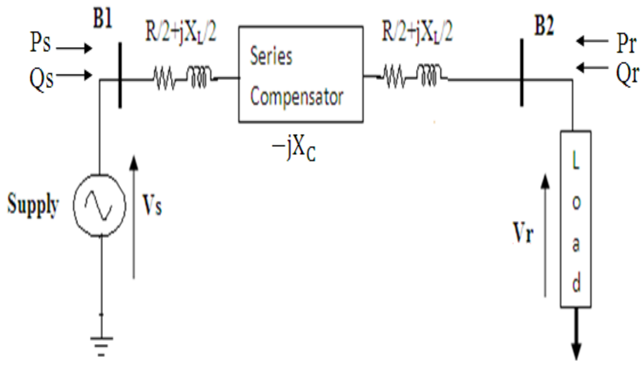

Fig-1: Series compensated power transmission corridor

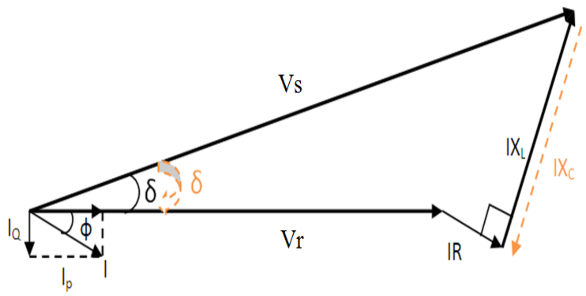

Fig-2: Phaser diagram

2.1 Stability Improvement

Power transmitted in system shown in Fig. 1 is given by

$$P = \frac{Vs * Vr}{X_L - X_C} \sin\delta \qquad (1)$$

Where
P - active power transfer
Vs - Sending end or Bus B1 voltage
Vr - Receiving end or Bus B2 voltage
δ - Angle between Vs and Vr
X_L - line reactance
X_C - series capacitive reactance

The effective transmission impedance with the series capacitive compensation is given by

$$X_L - X_C = (1-k)X_L \qquad (2)$$

Where, k is known as degree of compensation i.e.

$$k = \frac{X_C}{X_L} \qquad 0 \le k < 1 \qquad (3)$$

From Fig.2 and equations 1, 2, 3 it is clear that with increase in compensation level there is increase in capacitive reactance and ultimately angular stability and also power transfer capability.

2.2 Power Transfer Capability Improvement

From equation (1) it is evident that by decreasing the effective series reactance active power transfer can be increased.

2.3 Voltage Stability Improvement

Although series capacitors are not usually implemented for voltage control, they do contribute to improve the system voltage and reactive power balance. As magnitude of the total voltage across the series line inductance is increased by the magnitude of the opposite voltage, V_C is developed across the series compensator, due to the increase in the line current.

2.4 Degree of Compensation

The degree of compensation is defined by the ratio of capacitive reactance to the total inductive reactance of the transmission line given by equation (3).

At 100% compensation the effective line reactance would be zero and the line current and power flow would be extremely sensitive to changes in the relative angles of terminal voltages. In addition the circuit would be series resonant at the fundamental frequency. High compensation level also increases the complexity of protection circuit and probability of sub synchronous resonance. Therefore a practical limit to the series compensation is up to 75%.

3. SERIES CAPACITOR

Series capacitors have been used in transmission and distribution lines to compensate inductive reactance. The inductive reactance is reduced by the amount of inserted capacitive reactance. Series capacitor compensation is self regulating, that is, its reactive power output increases with the line loading. Series capacitors are ideally suited for effectively shortening long lines. Series capacitor reduces both the characteristic impedance and electrical length of line. As a result, both voltage regulation and stability are significantly improved.

3.1 Calculation of Series Capacitor

Series capacitor is used in line to reduce line reactance. Therefore,

$$Xc = kX_L \qquad (4)$$

Where, k is the degree of compensation

$$Xc = \frac{1}{2\pi fc} \qquad (5)$$

$$C = \frac{1}{2\pi f Xc} \qquad (6)$$

Series Compensation has following advantages,

1. Self regulating device.
2. Low risk of problems from load generated harmonics.
3. Control of loading of two parallel lines to minimise active and reactive losses.
4. Time overloading capability.

3.2 Location of Series Capacitor [3][4][5]

A series capacitor bank can theoretically be located anywhere along the line. Factors influencing choice of location include cost, accessibility, fault level, maintainability of series capacitor, protective relaying consideration, voltage profile and effectiveness in improving power transfer capability. When a series capacitor is to be installed in a transmission line mainly following locations are considered.

1. Midpoint of the line.
2. Line terminals
3. 1/3 or 1/4 points of the line

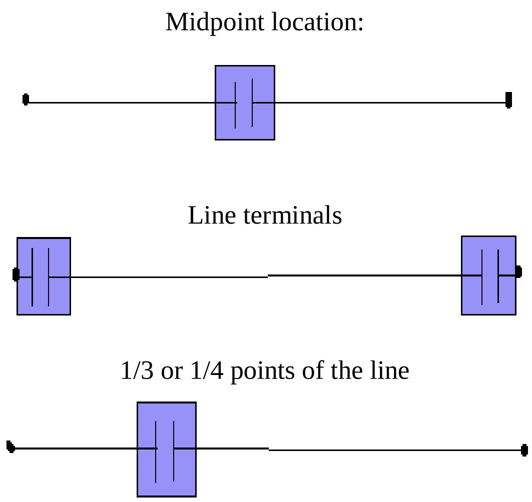

Fig-3: Typical series capacitors locations

The location of series capacitor banks is important for several reasons:
• The compensation "effectiveness" of the series capacitor varies as a function of the series capacitor location along the line.
• The series capacitor location affects the voltage profile along the line.
• The transmission line protection and the series capacitor main circuit equipment are affected by the series capacitor location.
• The series capacitor location affects the maintainability of the series capacitor.
• For MOV protected series capacitors, the rating of the MOV is very dependent upon the series capacitor location.
The midpoint location has advantage that the relaying requirements are less complicated. If compensation is less than 50% in addition short circuit current is lower, however it is not very convenient in term of access for maintenance, monitoring, securities.

4. PROBLEM FORMULATION

4.1 Bus Classification

Depending on the quantities that have been specified, the buses are classified into 3 categories.

Load bus (Type 1) - In a load bus, the real power (P) and the reactive power (Q) are known. The variables V and δ are not specified. So this bus is also called as PQ bus.

Generator bus/Voltage Controlled bus (Type 2) - In a generator bus, the voltage (V) is kept constant and the output power (P) is fixed. These two items are controlled by the excitation system and the governor. The unknown variables are Q and δ. So this bus is also called as PV bus.

Swing bus/Slack bus (Type 3) - At the reference generator or swing bus, the voltage (V) and the load angle (δ) are known. The unknown variables are P and Q

Therefore for load flow analysis three bus power system has been selected.

4.2 Power Flow Equation

A faster solution is obtained using the Newton Raphson method and is suitable for large-scale problems [9]. In this approach, the partial derivatives are used to construct the Jacobian matrix. For the three-bus problem, the bus power relations are given by:

$$P_1 = (Y_{11}V_1 + Y_{12}V_2 + Y_{31}V_3)V_1$$

$$P_2 = (Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3)V_2 \qquad 7$$

$$P_3 = (Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3)V_3$$

The elements of the Jacobian matrix based on equations are

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial V_1} & \frac{\partial P_1}{\partial V_2} & \frac{\partial P_1}{\partial V_3} \\ \frac{\partial P_2}{\partial V_1} & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_3} \\ \frac{\partial P_3}{\partial V_1} & \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_3} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \qquad 8$$

4.3 Power System

For the analysis of series compensation single phase system shown in Fig.4 has been selected and it is scaled down model of actual transmission line which is scaled down from 173 MVA to 8.66 KVA and 289 KV to 400 V for three phase line. In the scaled down model a line has resistance 0.0048Ω/km, inductance of 0.1 mH/km and shunt capacitance 0.1609µF/km. The line is made by connecting π networks in series and one π network is designed as equivalent circuit for 50 km line, having R=0.24Ω, L=5 mH and C=4 µF. For analysis of series compensation in mesh system three bus power system is modeled in Fig.4 and the impedances for these lines are mentioned in table 1. Here bus 1is slack bus having bus voltage 230V∠0, bus 2 taken as generator bus since another generator is connected to selected topology and bus 3 taken as load bus.

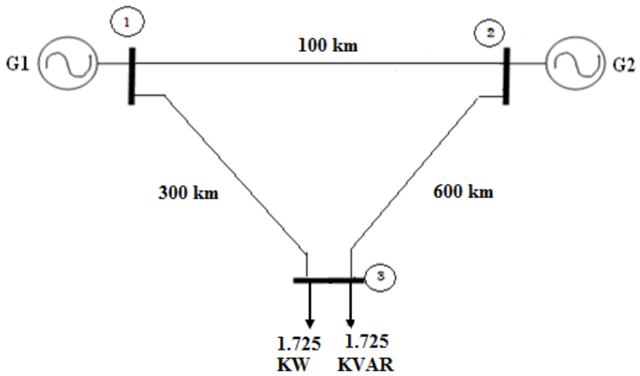

Fig-4: Three bus mesh power system

5. MATLAB SIMULATION RESULTS

In MATLAB simulink software, three bus power system modeled, simulated and load flow analysis has been done. If line 2-3 (600 km line) is, compensated then total electrical length of that line decreases. After compensation of line L2-3, power of line L1-2, L1-3 changes accordingly. It is verified by using simulation.

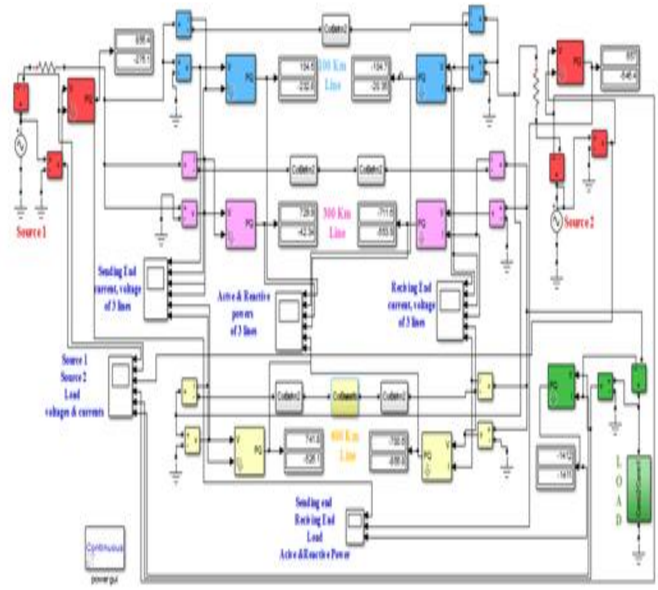

Fig-5: Simulation for 3 bus power system

Fig. 5 shows the simulation for 3 bus power system having line lengths 100 Km, 500 km and 600 km having line impedance, and required series capacitors for series compensation are mentioned in table (1).

Table-1: Impedance and series capacitors for 3 bus power system

Sr. No.	Length (km)	Impedance (Ω)	k=25% C (µF)	k=50% C (µF)	k=75% C (µF)
1.	100	0.48+ j3.14	4050	2027	1350
2.	500	2.4+ j15.7	810	405	270
3.	600	2.88 +j18.88	675	338	225

If we compensate 600 km line for 50%, means the electrical length of 600 km line becomes approximately 300 km. So the electrical lengths of line L1-3 and L2-3 becomes approximately equal. Due to this both lines have to carry approximately same power through them in compensation mode.

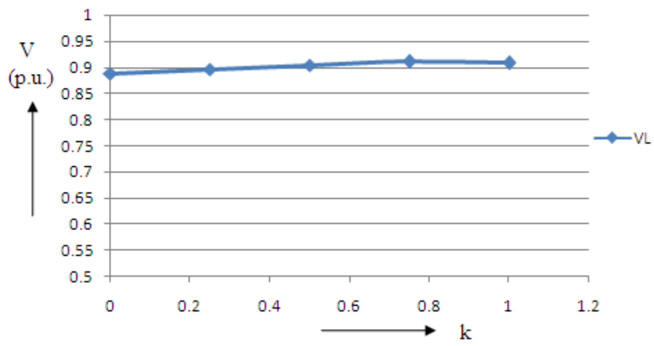

Chart-1: Effect of compensation level on system voltage

As the compensation increases the load end voltage (i.e. receiving end voltage) increases. This leads towards better voltage regulation. This statement is verified by chart (1).

Chart (2), (3) and (4) shows the result of power system when 600 km line is compensated at 50%. It shows that after compensation of 600 km line active power transfer in that line is increased; also power flow through the other lines is changed. After compensation impedance on L2-3 and L1-3 are approximately same so power in those lines is approximately equal which is verified by chart (2). Also due to the reduction in transmission impedance losses are also reduced.

Chart (3) and chart (4) gives the change in the current and reactive power flow, before and after compensation respectively.

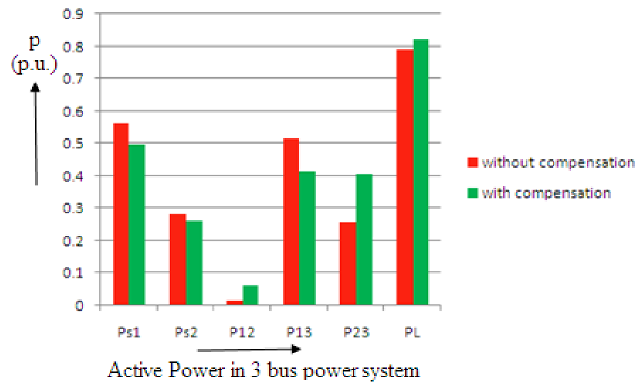

Chart-2: Effect of compensation on power transfer

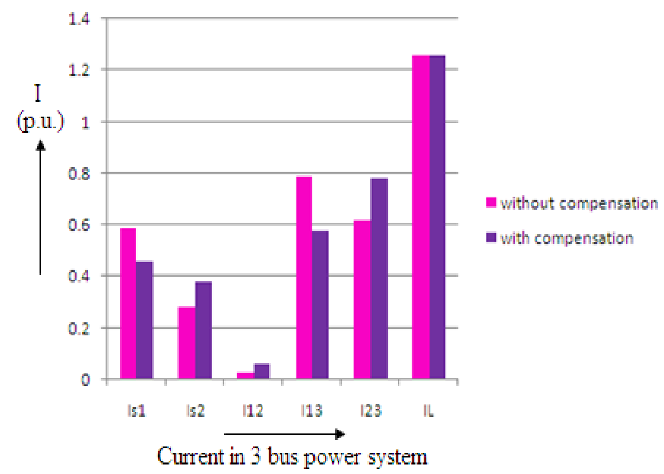

Chart-3: Effect of compensation on current flow in 3 bus power system

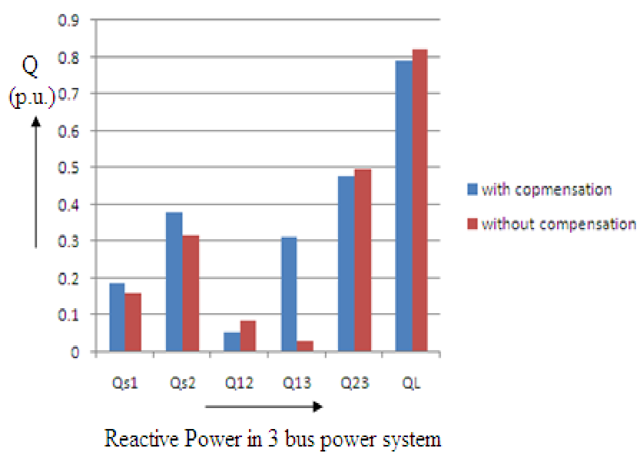

Chart-4: Effect of compensation on Reactive power flow in 3 bus power system

6. CONCLUSIONS

Series compensation is one of the methods of reactive power compensation. Location of series capacitor is an important issue. Series compensation improves line power handling capacity. In this paper three bus power system has been modeled and effect of series compensation for three bus mesh system is analyzed using MATLAB/SIMULINK. This paper concludes that series compensation is the effective means of improving electrical characteristics of transmission line. Voltage profile, power transmission capability, stability are enhanced by series compensation and mid of the transmission line is the best location for series compensation.

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BIOGRAPHIES

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