A review on Series Compensation of Transmission Lines and Its Impact on Performance of Transmission Lines

[1]Himanshu M. Joshi, [2]Nishant H. Kothari
[1]PG Scholar, [2]Assistant Professor
Electrical Engineering Department, MEFGI, Rajkot, India
[1]joshihimanshu777@gmail.com, [2]nishantkothari77@gmail.com

***Abstract*— Insertion of series capacitor in transmission line reduces net transfer reactance of line and it gives greater power transfer capability of the lines. It also improves power flow control & voltage regulation of lines. But it also causes problem to the conventional distance protection scheme during fault condition. The major problem to the distance relay is to measure correct impedance from relaying point to fault point when series capacitor remains in fault path. This paper briefly discusses need of series compensation, basic series capacitor model and problems due to series compensation**

***Keywords*−Series compensation, Capacitor bank protection, Over Reach, Under reach, Voltage inversion, Current inversion**.

I-INTRODUCTION

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 line capacity of existing lines. Use of series capacitors for compensation part of the inductive reactance of long transmission lines will increases the transmission line capacity. It also increases transient stability margins, optimizes load-sharing between parallel transmission lines and reduces system losses. Transmission line compensation implies a modification in the electric characteristic of the transmission line with the objective of increase power transfer capability. In the case of series compensation, the objective is to reduce the transfer reactance of the line at power frequency by means of series capacitors. This result is an enhanced system stability, which is evidenced with an increased power transfer capability of the line, a reduction in the transmission angle at a given level of power transfer and an increased virtual natural load. [1]

The fixed series compensations of lines are normally used for better utilization on the existing power transmission systems. It is presented as the best choice, because not only does it increase the power transmission capacity but also it stabilizes the interconnected networks by reducing net transmission line impedance. Also significantly increases the distance over which AC power can be transmitted. [2]

Series capacitors may be installed at one or both line ends. Line ends are typical capacitor locations, because it is generally possible to use space available in the substation only. In turn, this also reduces installation cost. Another possibility is to install the series capacitors at some central location on the line. Midpoint series compensation is more effective in case of very long transmission lines. Series capacitors located at the line ends create more complex protection problems than those installed at the center of the line. [4]

II- NEED OF SERIES COMPENSATION

Power transfer on EHV Lines:-

The Power along the transmission line is often explained by in terms of the system shown below figure 1.

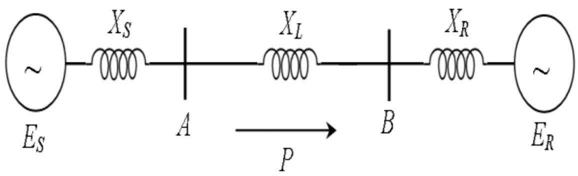

Fig-1 Transmission line without series compensation

The active power P transferred over the uncompensated transmission lines is given by

$$P=((Es*Er)/Xt)*\sin(\delta)$$

Where,

Es=Sending end voltage.
Er=Receiving end voltage
Xt=Transfer reactance of transmission line
δ = Load Angle.

Higher voltage gives higher power flow limit. Higher voltage for same power gives lesser current and lesser I^2R losses in line. The restricting factors on upper limit of transmission system voltage level are the design complexity, cost of equipment's and size of the conductor.

Method to improve transmission line power transfer capacity:-

1. **By connecting lines parallel.**

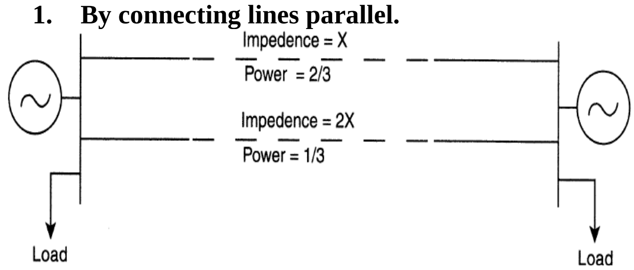

Fig-2 Power transfer using parallel lines.

As shown in Fig-2 power is transmitted by using two lines connected parallel to each other. As parallel transmission line reduces the net impedance of transmission line power transfer capacity increases. But there is a limit of maximum line loading capability with which a transmission line may operate. Increase in receiving end system load capacity to its normal capacity requires more no. of parallel connected lines. This increases cost and complexity of transmission system.

1. By using series compensation.

Series compensated transmission lines utilize series capacitors to cancel a portion of the inductive reactance of the transmission line, So by means of compensation it can improve the power transmission capability of the line. Series compensation has been applied mostly to long transmission lines and other locations where the transmission distances, are great and where large power transfers over these distances are required. [6]

Modern HV and EHV transmission lines are series compensated to improve power system performance, to enhance power transfer capacity, to enhance power flow control and voltage control and to decrease capital investment. [2]

The Power along the transmission line with series compensation is often explained by in terms of the system shown below figure 3.

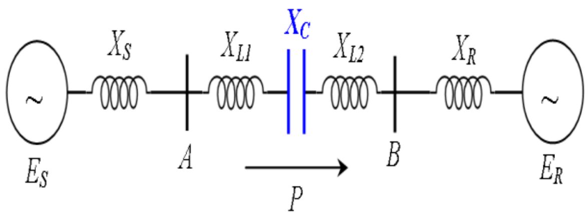

Fig-3 Transmission line with series compensation

The active power P transferred by the compensated transmission lines are computed as

$$P=((Es*Er)/Xt-Xc)*\sin(\delta)$$

III-TRANSMISSION LINE MODEL WITH SERIES COMPENSATION

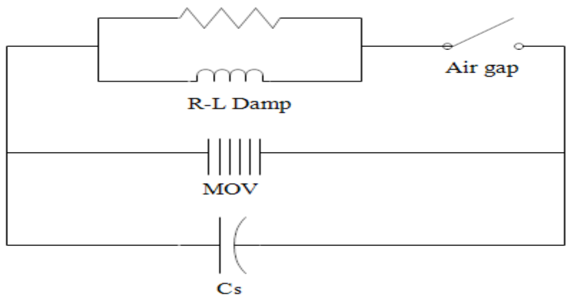

Fig-4 Series capacitor bank model

A series capacitor is not just a capacitor bank in series with the line. For proper functioning, series compensation requires control, protection and supervision facilities to enable it to perform as an integrated part of power system. Figure 4 represents typical circuit diagram of series capacitor unit. The types of capacitor bypass protection depends upon the approach taken by utilities. They are given as follows:

1. Metal oxide varistor (MOV) protection
2. Air Gap with R-L Damping

These all three types of devices located with parallel to capacitor bank protects the capacitor bank against over voltages during fault conditions.

1. Metal oxide varistor (MOV)

Primary protection system having characteristics of nonlinear type is called as varistor. The voltage current relationship can be given by following equation. [6]

V=K*(I^β)
V= varistor voltage
I= varistor current
β =a constant<1

At the time of fault due to large fault current value the voltage across capacitor bank increases. MOV is set to get conducted before the voltage across capacitor bank reaches to its maximum withstands voltage level. However, it is not feasible to leave this type of resistor permanently in parallel with the capacitor, as it would increase the losses. [6]

The metal oxide varistor (MOV), due to its greater non-linearity, is superior in its ability to limit the voltage across capacitor bank. In normal condition leakage current through the MOV is of the order of mili-amperes, which is considered as acceptable. The MOV devices provide several benefits, including instantaneous reinsertion, lower capacitor protective levels, high reliability, and low maintenance costs. MOV conduction level required to protect the capacitor bank is 2.5 times the nominal capacitor bank voltage [6]

2. Air gap with R-L Damping

The second type of capacitor bank bypass system is air gap system as shown in Figure 4. If fault level is very high and if it exceeds the maximum energy dissipated capacity level across MOV, it is required to protect capacitor bank along with MOV. Air gap flashes over at a particular voltage level. [6]

The voltage at which air gap conducts is 2.5 to 3.5 times the nominal capacitor voltage. The gap flashover occurs in a very few microseconds following a fault, which bypasses the capacitors bank completely. The air gap conduction is interrupted when the transmission line breakers operate to isolate an internal fault. For external faults, by some technique must be provided for extinguishing the gap conduction. [6]

This is sometimes accomplished by injecting compressed air through the gap to extinguish the arc. The injection of air is controlled by monitoring the current through the air gap. A forced-triggered gap may also be used. This type of gap ensures flashover at a given particular voltage of capacitor bank. The air breaker is also used by an operator to remove the capacitor bank from service for maintenance, and for reinserting the capacitor bank into service following these intentional removals. The air breaker is usually ordered to close when the gaps are fired, which provides a backup protection for the capacitor. [6]

The main disadvantage to this system is the complexity of the equipment and the fact that there may be some doubt regarding the successful reinsertion, which may be very important for system stability purpose and for restoring power transfer quickly.[6]

R-L damp system as shown in figure 4 is a current limiting circuit, usually consisting of an inductor and resistor in parallel. When the gap fires or the breaker closes, this device causes the current to limit at a frequency that depends on the value of inductance and capacitance of the circuit. The damping is such that it decays the current to a negligible value in less than one cycle of the fundamental frequency. [6]

Series Capacitor bank must be protected from the over voltages that occur due to flow of the high fault currents on the transmission line. Different protective responses are often designed for faults on the line that includes the series capacitor, which are designated as internal faults. Faults on other nearby lines are called externalfaults, and these more remote faults may require a different type of capacitor protection. [6]

IV-EFFECTS OF SERIES COMPENSATION

The main effects of series compensated line of long EHV transmission line are discussed below. [6]

1. The lower line impedance improves stability.
   When capacitor bank is inserted into the transmission line, the rotor angle (δ) reduces for the same amount of power transfer due the effect of compensation. Reduction in angle δ allows rotor to operate at a lower rotor angle with increased stability limit.
2. The lower line impedance improves voltage regulation.
   By inserting capacitor bank into the transmission line net impedance of the line reduces resulting into lesser voltage drop along the transmission line and better voltage regulation.
3. Adding series capacitance provides a method of controlling the division of load among several lines.
   By controlling degree of compensation of capacitor bank installed in a several bus system, amount of the load shared among the lines can be controlled. It gives the better control of load among several lines.
4. Increasing the loading capacity of a line improves the utilization of the transmission system and therefore the return on the capital investment.
   Series compensated transmission lines allow power transfer at the same voltage level over longer transmission lines than uncompensated lines. This better utilizes the existing transmission network, which is cost effective and quicker rather than building new or additional parallel lines
5. Increase power transfer capacity.
   As series compensated lines have reduced net transfer reactance, power transfer capability of system greatly increases compare to uncompensated line. This method of increasing power transfer capacity in the existing transmission system may eliminate the need of connecting parallel lines for increased load demand.

V-PROBLEMS DUE TO SERIES COMPENSATION

Insertion of capacitor bank in to the transmission line creates several problems to the protection scheme. Series compensation makes the protection scheme more complex. There are several problems that occur due to insertion of capacitor bank into the transmission line.

The problems are briefly discussed as [3], [4],[7]

1. Over reach and under reach

The settings of the distance relay are done on the basis of the positive sequence impedance between the relay location point and the fault location point. On the other hand the setting of ground distance relay is carried out on the basis of the zero phase sequence impedance. The corresponding distance or impedance from fault location to relay location is known as reachof the relay.

The insertion of capacitor bank into line creates certain complexities in application of impedance relay. Because of capacitive reactance Xc the fault after the capacitor looks nearer and thus therelay over-reachesdue to capacitive reactance.

That means the fault location is outside of the relays operating region but relay seen that fault into its operating region and operates.

It is possible to correct the setting of the relay if it is known that the capacitor is always going to be part of the fault circuit. However, during high current faults, the varistor conducts and the capacitor gets shorted. The extents up to which the MOV conducts and to what extent the capacitor bypasses depends on the magnitude of the fault current. Thus, the degree of over-reaches due to series compensation is highly uncertain.

The close-in faults (faults just after the capacitor bank) can appear to be a fault behind the relay, as these types of faults the net impedance seen by relay is capacitive. Thus relay under-reaches due to capacitive reactance Xc.

That means the fault location is inside of the relays operating region but relay seen that fault as outside of its operating region and does not operate.

2. Voltage inversion and current inversion

Voltage inversionis the phenomena that the relay sees the fault on the protected transmission line in the reverse direction or the change of 180° in the voltage phase angle. This can be explained in the below figure 5.

Here a series compensated transmission line is shown, where the SC is located in the substation. Now consider a fault occurring after capacitor bank.

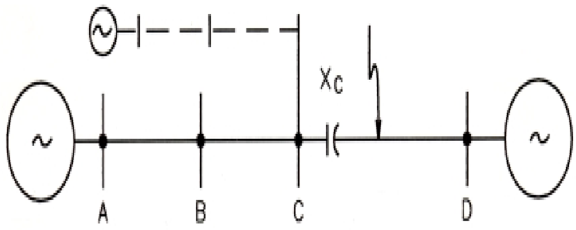

Fig- 5 Voltage inversion

Relays see an inverted or reverse voltage at the location of fault. In other word relay see this fault as a reverse fault. If the impedance from the relay to the fault is Capacitive rather than inductive then voltage inversion will occur. Voltage inversion may affect both directional and distance elements. Thus depending on the location of the fault, the relay sees a fault to be a forward or a reverse one.

Now at a particular bus the condition for the voltage inversion assuming negligible resistance in the fault loops are as follows

$$X_c > mX_L$$
$$X_c < mX_L + X_A$$

Xc is the line capacitance
X_L is the inductive reactance
m is the fault location in pu
X_A is the reactance of source A

Condition specify that net impedance from bus C to fault location is capacitive and from bus A to Bus C is inductive so at bus C voltage reversal will occur.

A current inversion occurs in a series compensated transmission line, for an internal fault, the equivalent system at one side of the fault is capacitive and the equivalent system at another side of the fault is inductive. The current flows out of the line at one terminal, which is referred to as current out feed.

In case of current inversion relay sees fault current in the reverse direction because of large capacitive reactance in the fault loop. The voltage and current inversion cannot happen simultaneously. For figure 6 the condition for current inversion assuming only reactance in the fault loop is given as follows:

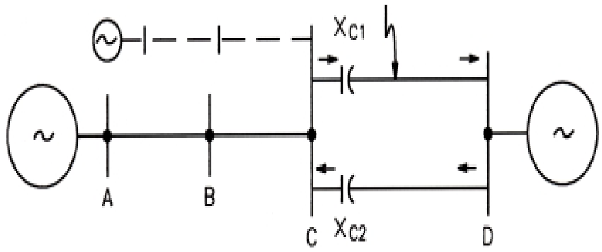

Fig. 6 current inversion

$$X_c > mX_L + X_A$$
$$V_c = (X_c\{X_c-(mX_L+X_A)\}*V_A) < V_{max}$$
V_{max}=voltage that causes the gap to flash

Current inversion may occur for the faults closer to the relay and for system having small source impedance. The possibility of current inversion reduces under the conduction of MOV due to the reduction of capacitive reactance to X_{CMOV}, Which is less than X_c .The current inversion and voltage inversion depend on the location of SC installation on the line.

For the high-current faults, the air gap or MOV bypasses series capacitor bank. Current inversion is a rare event for these high current faults. However, for high-resistance faults, the low fault current may not allow the capacitor bypassing scheme and creates the conditions for a current inversion. When X_C is approximately equal to the system reactance X_S, the current contribution to the fault at the right end of the transmission line approaches zero. This creates protection and fault-type selection problems.

3. System Transients

In a series compensated transmission line when fault occurs at the remote end with series capacitor as a part of fault loop gives rise to ac transient current component along with steady state ac component of fault current. The frequency of such ac transient component is sub-harmonic frequency and is given by. [3]

$$\text{Fundamental Frequency}*(X_C/X_L)^{1/2}$$

Where X_C is total capacitive impedance in series with line inductive reactance X_L. Distance relay response during positive and negative half cycles of fault current is different due totransient ac component of fault current and makes it difficult for relay to exactly identify the fault location. [3]

VI-CONCLUSION

Insertion of a series capacitor bank into the transmission line increases power transfer capability, improves stability margin, better voltage regulation and better control over the division of load. Series capacitor bank is protected against over voltages by MOV and Air gap trigger circuit during high fault currents. During fault conditions when series capacitor remains in faulted loop, distance relays do not responds correctly and measures incorrect impedance resulting into overreaching or under reaching of distance protection scheme.

REFERENCE

[1] AbdolamirNekoubin "Simulation of Series Compensated Transmission Lines Protected with Mov" World Academy of Science,Engineerin and Technology 58 2011

[2] ZELLAGUI Mohamed, CHAGHI Abdelaziz "Impact of Series Compensation Insertion in Double HV Transmission Line on the Settings of Distance Protection" International Journal of Scientific & Engineering Research Volume 2, Issue 8,August-2011 ISSN 2229-5518

[3] Stan Wilkinson "Series Compensated Line Protection Issues" GE Power Management 215 Anderson Ave. Markham, Ontario, Canada L6E 1B3

[4] Héctor J. Altuve, Joseph B. Mooney, and George E.Alexander Advances in Series-Compensated Line Protection". *Schweitzer Engineering Laboratories, Inc.*

[5] G. E. Alexander S. D. Rowe J. G. Andrichak S.B. Wilkinson "Series Compensated Line Protection –A Practical Evaluation" GE Power Management
[6] P.M. Anderson "Power System Protection" Wiley-Interscience, a John Willey & Sons, Inc., Publication, Chapter-15 Series-Compensated Line Protection. Page no. 575-642.
[7] BhaveshBhalja, R.P.Maheshwari, Nilesh G. Chothani "Protection and Switchgear", OXFORD UNIVERSITY PRESS. Chapter -3 Pilot independent Distance Relaying Scheme, Page no. 82-119.