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Determination of Optimal Account and Location of Series Compensation and SVS for an AC Transmission System

B.Suresh Kumar
Asst.Professor-CBIT-Hyderabad

ABSTRACT:

The paper mainly concentrates on the latest development of compensation using Series Capacitor and SVS (Static VAR System).

The above concept to full extent in terms of advantages of the above mentioned compensation and to express the disadvantages of the concept along with the remedies. The paper involves universal software (C Language) programming developed for finding the optimal amount and location of compensation and SVS for an AC transmission system for any length of AC transmission line of any extra high tension voltages.

In this work optimal location of the series compensation and SVS has been determined for a given transmission system. We derived the generalized expressions for Maximum receiving end power, Compensation efficiency and Optimal value of series compensation have been developed in terms of the line constants and capacitive reactance used for different schemes of series compensation. Based upon steady state performance analysis, it is determined that the compensation scheme in which series compensation and SVS are located at the mid point of the transmission line yields Maximum receiving end power and Maximum Compensation Efficiency.

Comparison criteria based upon the Maximum Power Transfer $P_{R(max)}$ *over the line has been developed. The generalized expressions for the optimum value of series compensation has been derived and hence the optimum value of series compensation has been determined for various cases of Series Compensation the criteria of* $P_{R(max)}$ *and compensation efficiency* $\eta_{c.}$ *have been utilized for assessing the optimal location of series and shunt compensation. Based upon the studies performed in case 5, mid point location of Series Compensation and SVS which yields the Maximum Receiving end Power* $P_{R(max)}$ *and Compensation Efficiency* ηc.

I. INTRODUCTION

LONG DISTANCE TRANSMISSION LINES: In early days, the electric power was mainly used for electric lighting and the power was obtained from the steam power stations which are located very close to the load centers. Later, with the development of industry, demand for large amounts of power grew. Bulk power stations had to be constructed in order to meet the growing demand for large amounts of power. As the capacity of the steam power station grew, it became necessary, from the point of view of economy, to erect them where the fuel and water were most easily obtained. Therefore, the site of power stations was, sometimes far away from the load centers and the necessity of transmission lines for carrying power thus came into existence.

As the distance of transmission became high, various factors affecting transmission capacity arose. The important ones amongst them are:

1. Active loss in the transmission line
2. Reactive loss and the voltage drop in the line
3. Stability

1.2 COMPENSATION OF TRANSMISSION LINES:

"Compensation" means the modification of the electrical characteristics of a transmission line in order to increase its power transmission capacity while satisfying the fundamental requirements for transmission namely, stability and flat voltage profile.

1.3 TYPES OF COMPENSATIONS:

The compensation of transmission system is broadly classified as follows:

1. Surge impedance compensation
2. Line length compensation
3. Compensation by sectioning

1.3.1 SURGE IMPEDANCE COMPENSATION:

A flat voltage profile can be obtained if the surge impedance of the line is changed, by suitable compensation, to a value Z_0 so that the surge impedance loading, then is equal to the actual load. This type of compensation should be ideally capable of variation with quick response. This type of compensation, whose primary function is to modify the value of the surge impedance, is called the surge impedance compensation.

1.3.2 LINE LENGTH COMPENSATION:

Controlling the virtual surge impedance to match a given load is not sufficient by itself to ensure stability of transmission over longer distance hence line length compensation is used to improve the stability.

For a loss less line, the sending end and receiving end quantities are related by the following equation.

$$V_s = V_r\, Cos\theta + jZ_0 \frac{(P_r - jQ_r)}{V_r}\, Sin\theta$$

Equating imaginary parts of the above equation, we get

$$P_r = \frac{V_s V_r}{Z_0 Sin\theta} Sin\delta$$

Where ‘δ’ is the power angle of the line. From the above equation, it can be seen that the stability can be improved by decreasing either the surge impedance (Z_0) or the electrical length ‘θ’. Usually ‘θ’ is decreased to improve stability. The value of ‘θ’ is decreased by using series capacitor. This type of compensation is called “line length compensation” or “θ compensation”.

1.3.3 COMPENSATIONBY SECTIONING:

The line is divided into a number of sections by connecting constant voltage compensations at intervals along the line. Constant voltage compensators are compensating equipment which attempt to maintain voltage constant at their location. The maximum transmissible power is that of the weakest section. However, this section being shorter than the whole line, an increase in maximum power and stability results. The type of compensation is called compensation by sectioning or dynamic compensation.

II. TYPES OF COMPENSATORS

2.1PASSIVEANDACTIVE COMPENSATORS :

“Passive Compensators” include shunt reactors, shunt capacitors and series capacitors. These devices may be either permanently connected or switched, but in their usual forms they are in capable of continuous (i.e., steeples) variation. They operate is essentially static. Apart from switching they are uncontrolled.

“Active compensators” are usually shunt connected devices which have the property of tending to maintain a substantially constant voltage at their terminals. They do this by generating or absorbing precisely the required amount of corrective reactive power in response to any small variation of voltage at their point of connection. They are usually capable of continuous variation and rapid response. Control may be inherent, as in the saturated, reactor compensator, or by means of a control system, as in the synchronous condenser and thyristor controlled compensators.

2.2 SERIES COMPENSATION:

The series compensation will reduce the reactance of the line by means of series capacitors. This increases the maximum Power, reduces the transmission angle at given level of power transfer and increase the virtual natural load. The line reactance now absorbs less of the line charging reactive power, often necessitating some form of shunt inductive compensation.

$$P = \frac{V^2}{X} Sin\delta$$

The voltage drop ΔV due to series compensation is given by $\Delta V = IR\, Cos\Phi_r + I\,(X_L\text{-}X_C)\, Sin\Phi_r$

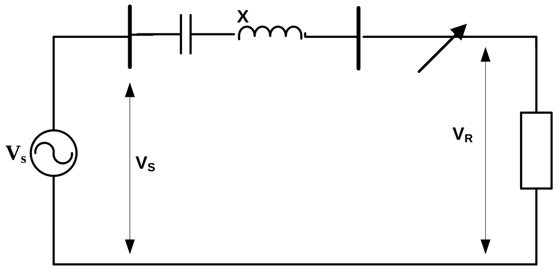
Here X_C = Capacitive reactance of the series capacitor bank per phase and X_L is the total inductive reactance of the line per phase. In practice, X_C may be so selected that the factor $(X_L\text{-} X_C)\, Sin\Phi_r$ becomes negative and equals $RCos\Phi_r$ so that ΔV becomes zero. The ratio X_L/X_C is called “compensation factor” and expressed in percentage known as the “Percentage Compensation” or Degree of compensation”.

2.2.2 VOLTAGE STABILITY:

A simple radial system with feeder line reactance 'X', series compensation reactance X_C and load impedance Z is shown in figure below. The corresponding normalized terminal voltage 'V_r' versus power 'P' plots, with unity PF load at 0%, 50% and 75% series capacitive compensation.

$$P = \frac{V^2}{X_L - X_c} Sin\delta$$

Circuit Diagram :



2.2.3 LOCATION OF SERIES CAPACITORS:

The effect of series capacitor on a circuit is from its point of location towards load end. Hence on a radial feeder, series capacitor must be located at source and load whose voltage is to be improved. If there are number of tapped loads distributed throughout, the rule of thumb for the best location of series capacitors is at, about one third of electrical impedance of the feeder from source bus.

2.2.4 RATINGOFSERIES CAPACITORS:

The rating have to determined for series capacitors i.e., KVAR, voltage and current. As series capacitor has to carry full line current in the circuit where it is inserted, its continuous current rating should be at least equal to peak line current and preferably greater than the peak line current for the purpose of catering further load growth. The value of Xc depends upon the percentage of compensation required. The voltage rating is (IX_c) and KVAR rating per phase is ($3I^2X_c$).

2.2.5 APPLICATIONS:

1. Improved system steady state stability.
2. Improved system transient stability.
3. Better load division on parallel circuits.
4. Reduce voltage drops in load areas during severe disturbances.
5. Reduced transmission losses.
6. Better adjustment of line loading.

7.2.3 SHUNT COMPENSATION:

For shunt compensation, shunt reactors, synchronous condensers and shunt capacitors are extensively used. In addition to these, a thyristor controlled static shunt compensator to meet reactive power generation and absorption demand has appeared in recent years. The most typical reasons for shunt compensation in EHV lines are explained below.

One primary reason for using shunt reactors or reactive control devices on EHV lines is to control steady state over voltage when energizing the long EHV lines or when operating under light load conditions. If shunt reactors are not used, the reactive power generated by line capacitance can cause high voltages at the receiving end of the line. However, to restrict insulation stresses caused by over voltage following sudden load rejection a substantial part of the shunt reactive compensation is usually left permanently connected.

2.3.1 PASSIVESHUNTCOMPENSATION:
CONTROL OF O.C VOLTAGE WITH SHUNT REACTORS

Passive shunt reactors are used to control the voltage at the receiving end of open circuited line. If these reactors could be uniformly distributed along the length of the line, then it is possible to get a flat voltage profile, with reduced surge impedance loading. However in practice, they cannot be uniformly distributed. Instead, they are connected at the end of line and at intermediate points, usually at intermediate switching stations. In case of very long line, some of the shut reactors are permanently connected to the line in order to provide maximum security against over voltage problem is less severe and the reactors are switched in or out frequently as the load varies. Shunt capacitors are usually switched type. If there is a sudden load rejection or open circuiting of the line, it may be necessary to disconnect them quickly to prevent them from increasing the voltage further and also to reduce the likelihood of ferroresonance where transformers remain connected.

2.4 STATIC VAR SYSTEM (SVS):

A static VAR system as per IEEE definition is a combination of static compensators and mechanically switched capacitors and reactors whose operation is coordinated. A static VAR system is thus not a well defined compensating arrangement because it is does not have a uniform V-I characteristics and its overall response time is greatly dependent on the mechanical switching devices used.

2.4.1 CONFIGURATION OF SVS:

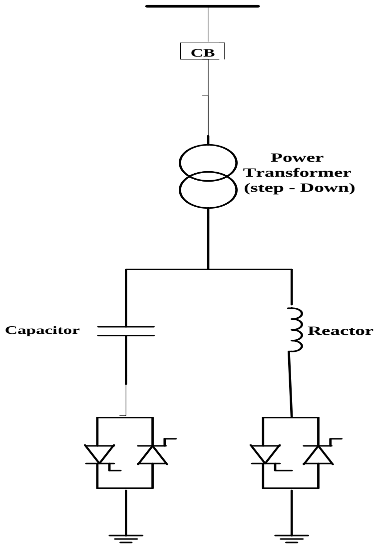
In conventional shunt compensation schemes shunt reactor is switched on during low loads and shunt capacitors are switched on during heavy loads or low lagging power factor loads.

In SVS, the compensation is controlled by any of the following:

1. Thyristor Switched Capacitors (TSC)
2. Thyristor Controlled Reactors (TCR)
3. Thyristor Switched Capacitors combined with Thyristor Controlled Reactors (TSC/TCR)

III. COMBINED TSC/TCR SVS:

In case of EHV transmission systems, the compensation requirements demand shunt capacitors during high loads and shunt reactors during low loads. Depending upon the desired control range of reactive power compensation required, thyristor controlled compensation is built up using a suitable combination of “Thyristor Switched Capacitors (TSC)” and “Thyristor Controlled Reactors (TCR)”.



2.4.4 CONTROL SYSTEM FOR SVS:

The amount of sophistication required for control system of SVS depends on application.

1.Voltage control
2.VAR flow control

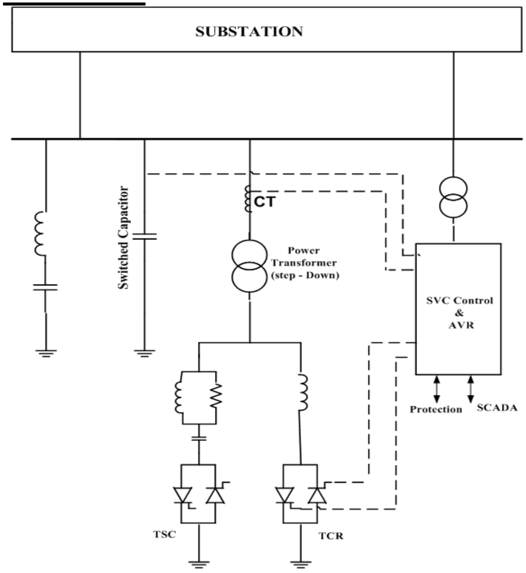
Referring to figure below, the bus bar voltage (V) and current flowing into the compensator (I) are both sensed y means of VT and CT. Both these values are fed to the Automatic Voltage Regulator (VAR).

AVR inn SVS is programmed to regulate transmission bus voltage with preselected tolerances and time delays.

The AVR and
Automatic VAR compensator performs the following tasks:

1. Controls phase angle of thyristor in SVS. SVS control is integrated with substation protection and SCADA system (Supervisory Control And Data Acquisition)
2. As the transmission voltage varies with load, the AVR performs the function of current control of flowing through the reactor R during each half cycle via the thyristor (Th). Smoothing Reactors (SR) provides a smoothing effect for current flowing through capacitor branches.

DIAGRAM:



GENERALISED EXPRESSION

3.1 REPRESENTATION OF LINES:

A transmission line is a set of conductors being run from one place to another supported on transmission towers. Such lines have four distributed parameters series resistance, inductance, shunt capacitance and conductance. It is observed that is very important in representing the lines of different lengths. It is to be noted that the electrical power is being transmitted over the overhead lines at approximately the speed of light. In order to get one full wave variation of voltage or current on the line the length of the line for 50Hz supply will be given by

$$f.\lambda = v$$

Where f is frequency of supply, λ is the wave length.

Transmission lines are normally 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 part network, where in the sending end voltage Vs and current Is are related to the receiving end voltage V_R and I_R through ABCD constants as

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_s \\ I_s \end{bmatrix}$$

Also the following identity holds for ABCD constants:

$$AD\text{-}BC = 1$$

These constants can be determined easily for short and medium length lines by suitable approximations lumping the line impedance and shunt admittance. For ling lines exact analysis has to be carried out by considering the distribution of resistance, inductance and capacitance parameters and the ABCD constants of the line are determined.

3.2 ABCD LINE PARAMETERS OF TRANSMISSION LINE:

For long transmission lines sending end and receiving end relations given by

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} COSh\gamma l & Z_c Sinh\gamma l \\ \frac{1}{Z_c} Sinh\gamma l & COSh\gamma l \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

A = D = Coshγ 1

B = Z_C Sinhγ 1

C = $(1/Z_C)$Sinhγ 1

Where $Z_C = \sqrt{\frac{Z}{Y}}$

$$\gamma = \sqrt{YZ} = Propagation\ constant$$

$$= \propto\ + j\beta$$

$$\propto\ = Attenuation\ constant$$

$$\beta = Phase\ constant$$

$$A = Cosh\gamma 1 = 1 + \frac{\gamma^2 1^2}{2} + \frac{\gamma^4 1^4}{24} + \ldots\ldots\ldots\ldots\ldots \approx \left(1 + \frac{YZ}{2}\right)$$

$$Sinh\gamma 1 = \left[\gamma 1 + \frac{\gamma^3 1^3}{6} + \frac{\gamma^5 1^5}{120} + \ldots\ldots\ldots\ldots\ldots\right] \approx \sqrt{YZ}\left(1 + \frac{YZ}{6}\right) \quad B = Z_C\ Sinh\gamma 1 = Z\left(1 + \frac{YZ}{6}\right)$$

$$C = \frac{1}{Z_C} Sinh\gamma 1 \approx Y\left(1 + \frac{YZ}{6}\right)$$

3.3 MAXIMUM RECEIVING END POWER :

The receiving end complex power in terms of generalized A_0 B_0 C_0 D_0 line parameters. Where A_0,B_0,C_0,D_0 are the ABCD parameter of the line after the compensation.

$$P_R = \frac{|V_S||V_R|}{|B_0|} COS(\beta - \delta) - \left|\frac{A_0}{B_0}\right| |V_R^2| COS(\beta - \alpha) \ldots\ldots\ldots\ldots (3.1)$$

Where $A_0 = |A_0|\angle\alpha \text{ and } B_0 = |B_0|\angle\beta$

P_R will be maximum at $\delta = \beta$

Such that,

$$P_{R(max)} = \frac{|V_S|\,|V_R|}{|B_0|} - \frac{|A_0|}{|B_0|}|V_R|^2 COS(\beta - \alpha) \ldots\ldots\ldots\ldots (3.2)$$

In practical situations α is very small

Therefore, neglecting α

$$P_{R(max)} = \frac{|V_S|\,|V_R|}{|B_0|} - \frac{|A_0|}{|B_0|}|V_R|^2 COS\beta \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Substituting $|V_S| = K\,|V_R|$

$$P_{R(max)} = \frac{|V_R|^2}{|B_0|}\ \{K - |A_0| COS\beta\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

3.4OPTIMUMVALUEOFCAPACITIVE REACTANCE :

The generalized expression based upon the equation (3.4) derived in terms of the series capacitive reactance (X_C) used in each case. The optimum value of series capacitive reactance $X_{C(opt)}$ is determined by:

$$\frac{dP_{R(max)}}{dX_C}$$

3.5 COMPENSATION EFFICIENCY:

The compensation efficiency η_C is defined as the ratio of net reduction in transfer reactance to the series capacitive reactance used. Thus the effective series capacitive reactance X'_C (as compared to the actual value of X_C) is given by

$$X'_C = \eta_C X_c$$

Therefore,

$$\eta_C = \frac{Net\ reduction\ in\ transfer\ reactance}{Series\ capacitive\ reactance\ used} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Based upon the equation (3.6) the generalized expressions for the compensation efficiency are derived for series and shunt compensation location.

3.5 DEGREE OF COMPENSATION:

Degree of compensation is defined as it is the ration of capacitive reactance and the line inductive reactance it given by

$$K = \frac{X_C}{X}$$

For better understanding we re-call the formula

$$P_1 = \frac{|V_1| \quad |V_2|}{X} SIN\delta$$

With series capacitor, we get

$$P'_1 = \frac{|V_1| \quad |V_2|}{(X - Xc)} SIN\delta$$

from the above equations we get increase in power transmission $P_{increase}$

$$P_{increase} = P'_1 - P_1 = \frac{K}{1-K} P_1$$

Increase in the lengths of transmission lines and in transmission voltages, decrease in series capacitor costs.

Series capacitors can be located either in the lines or intermediate sub-stations or switching stations. Line location has many advantages such as better voltage profile along the line and reduced short circuit current contributes to a much simpler protection of the capacitors.

5.3 RESULTS:

(1)IE (I) DATA:

Case number	$P_{R(max)}$	$\eta_{C(opt)\%}$	$X_{C(opt)}$(p.u)	$S_{(opt)\%}$
1	18.48	78.47	0.108	88.76
2	21.52	89.52	0.099	81.84
3	23.56	78.47	0.116	95.64
4	14.62	92.44	0.096	79.42
5	17.53	95.50	0.096	80.00
6	16.52	84.82	0.108	90.00
7	13.25	90.00	0.096	80.00

(2)KHAMMUM-VIZAG LINE DATA:

Case number	$P_{R(max)}$	$\eta_{C(opt)\%}$	$X_{C(opt)}$(p.u)	$S_{(opt)\%}$
1	34.38	93.52	0.055	81.28
2	36.76	96.78	0.054	80.18
3	37.73	93.52	0.056	83.60
4	37.73	98.14	0.051	76.02
5	61.47	99.11	0.059	88.29
6	48.32	96.32	0.062	86.12
7	37.73	95.23	0.043	72.31
8	37.38	93.53	0.055	81.28

CONCLUSIONS

In the presented paper, comparison criteria based upon the Maximum Power Transfer $P_{R(max)}$ over the line has been developed. The generalized expressions for $P_{R(max)}$ in terms of A,B,C,D constants and capacitive reactance (X_C) are derived for the series compensated line. The generalized expressions for the optimum value of series compensation have been derived and hence the optimum value of series compensation has been determined for various cases of series compensation. The criteria of $P_{R(max)}$ and compensation efficiency have been utilized for assessing the optimal location of series and shunt compensation. Based upon the studies performed (case 5) midpoint location of series compensation and SVS is recommended which yields the Maximum Receiving end Power $P_{R(max)}$ and Compensation Efficiency η_c

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