Series Compensation on 400kV Transmission Line - A Few Design Aspects

R.N.Nayak, Y.K.Sehgal and Subir Sen

Abstract - **Indian Power System is characterized by vast 400kV long distance transmission network spread over all the Regions. Power transfer capacity of the long 400kV AC lines is restricted by their stability limit which is less than thermal capacity of the line leads to sub-optimal utilization of infrastructure. Series compensation on 400kV lines offers techno-economically attractive option to optimal utilization of infrastructure. This paper presents various network and design aspects as well as studies considered for the installation of series compensation on 400kV lines. Further, series capacitors being placed in series with the line, needs special attention in design and its protection which are described in details with specific reference to 400kV East-West inter-regional link.**

Index Terms- **MOV, Series Compensation, Tr. Line, TCSC**

I. INTRODUCTION

INDIAN power system is primarily dominated by vast 400kV lines, the backbone transmission network. The entire power system is demarcated into five Regional Grids viz. Northern, Western, Southern, Eastern and North-eastern Regions having total installed capacity of about 112,000MW with peak demand of about 86,000MW. The demand is expected to increase to about 157,000MW by the year 2011-12, which is almost double the existing demand. The uneven disposition of energy resources, which are mainly concentrated in a few pockets result into development of large number of long distant 400kV AC lines between generation resources and far-off load centres.

Power transfer capacity of the long 400kV AC tr. lines are restricted by their stability limit– much less than thermal capacity of the line(maximum allowable loading). Therefore, to ensure development of power system in an economical as well as environment friendly manner, it is necessary to utilize the existing transmission infrastructure to the maximum extent possible, so that the delivered power to the ultimate consumers would be available at an affordable price. Series Compensation on the 400kV lines is one of the techno-economic options to optimally utilize the existing infrastructure.

In India, a large number of series compensation on 400kV transmission lines have been installed/planned in the form of fixed and variable type of compensation.

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Extensive studies have been carried out to identify the candidate line as well as degree of series compensation and their type. In this paper, various network and design aspects of the series compensation installation on 400kV lines are presented. Further, series capacitors being placed in series with the line, requires special attention in its design and protection to ensure its high reliability and availability in the system which are described in detailed with specific reference to 400kV East-West inter-regional link. The application and benefits of series compensation are also deliberated.

II. SERIES COMPENSATION-USAGE AND BENEFITS

Series Compensation is basically putting EHV capacitors in series with transmission lines. The capacitor compensate the inductive reactance of transmission line, thereby making virtual reduction in line length and enhances the stability limit and power transfer capacity. Application of series compensation and its benefits in EHV transmission network are as given below:

- Increases the loadability of long line upto its thermal capacity
- Acts as a self-regulating device for better voltage regulation
- Reduces overall system losses
- Improves network stability – both voltage & angular stability
- Enables balanced power sharing between parallel lines so as to achieve best possible utilization of transmission lines

III. TYPE OF SERIES COMPENSATION

Series Compensation is broadly categorized in two types viz. fixed and variable compensation. Though very useful indeed, Fixed Series Compensation is limited in their flexibility. With the advent of power electronic devices like Thyristor and associated controls, the usefulness of controlled series compensation has been widened additionally. With Thyristor Controlled Series Capacitor (TCSC), it is possible to vary the degree of compensation with rapidity, limited only by the speed of response of the electronic scheme used. This opens up for applications previously not encountered in conjunction with Series Compensation, such as post-contingency power flow control, damping of power oscillations and Subsynchronous Resonance (SSR) mitigation.

A. Thyristor Controlled Series Compensation (TCSC)

Thyristor Controlled Series Compensation (TCSC) basically comprises a Series Capacitor in parallel to a Thyristor Controlled Reactor (TCR). By varying the firing angle of thyristor (to make the switch on/off), TCSC can optimize their degree of compensation over a wide range under various network conditions, hence the level of firm power delivered through a specific line can be controlled[1]. A schematic of TCSC is shown at Fig. 1 given below:

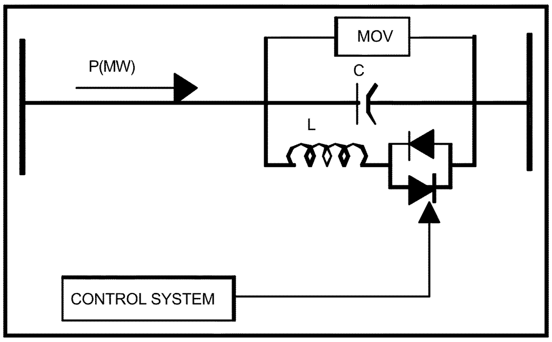

Fig-1: TCSC composition

Operationally, with the Thyristors firing, the TCR branch circulates current pulses, which add in phase with the line current. This "boosts" the capacitive voltage beyond the level that would be obtained by the line current alone.

Due to its inherent characteristic, TCSC is capable of quick control and distribution of active power flow through several parallel transmission lines to the secure transfer capability whenever required. In case of two different networks connected by weak inter-area links (less number of transmission lines), TCSC helps in damping out active power oscillations (inter-area mode) caused by any disturbances. In this way, TCSC introduces flexibility of power transfer in AC system like HVDC but at a nominal cost. A typical impedance characteristic of the TCSC is shown at Fig. 2.

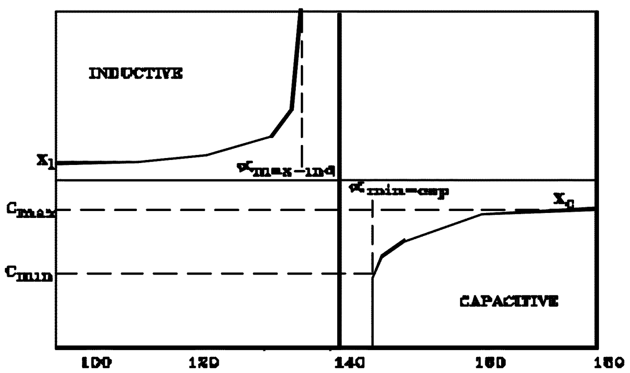

Fig 2: TCSC Impedance characteristics

For designing the range of TCSC reactance, dynamic studies are to be carried out considering worst contingent condition. Based on this, boost level is decided, which is a measure of the amount by which the reactance of the Controlled Series Capacitor can be virtually augmented to counteract power oscillations[2].

Further, TCSC is to be designed to operate under steady state with a relatively low nominal boost factor due to:

- Low overrating of the capacitor bank as the capacitor current increases (line current plus thyristor branch current) with increased boost at any given inserted voltage
- Thyristor losses and Harmonic generation increases with increased boost levels

TCSC can also overcome the problem of Sub-Synchronous Resonance (SSR) by changing its apparent impedance (as seen by the line current) for subsynchronous frequencies such that prospective sub-synchronous resonance is avoided. The associated control system operates on the Thyristor circuit in such a way that it makes it as a variable capacitor at fundamental frequency and a "virtual inductor" at sub synchronous frequencies.

B. Series Compensation on East-West Inter-regional link

As a step towards formation of National Grid, a synchronous interconnection between Eastern and Western Region has been implemented by commissioning of 400kV Rourkela (Eastern Region) – Raipur (Western Region) double circuit (D/c) line. However, due to long length of this line (about 412 kms) application of 40% series compensation has been planned to enhance the power transfer capacity of the inter-regional link at a marginal investment, which is under advance stage of implementation. Further, it was observed that during high order of power exchange over this link, certain contingency conditions like fault on the line etc. may lead to low frequency inter-area oscillations thus affecting system stability. Therefore, to damp out inter-area oscillations, variable series compensation in the form of Thyristor Controlled Series Capacitors (TCSC) has also been planned.

IV. SELECTION OF TRANSMISSION CORRIDOR AND DEGREE OF COMPENSATION

Identification of Tr. corridor for application of series compensation and determination of its degree is the first basic step while designing parameters for Series Compensation on EHV lines. As discussed earlier, application of series capacitor is beneficial for long lines where power transfer capacity is restricted by the stability limit and series compensation enhances the line loadability towards thermal limit. At the same time, it is necessary to ensure that in the event of outage of compensated line, parallel lines in the same corridor should be sufficient to cater the outage with reliability and security. Hence, based on the network configuration and power transfer requirement over certain transmission corridor, extensive load flow studies need to be carried out in identifying the candidate line.

After, selecting the line, next step is to determine the degree of compensation, which is defined as the ratio of capacitive reactance and line inductive reactance. This is a very important design parameter and should be selected judiously, as otherwise over compensation can lead to unnecessary commercial and technical impact.

Following aspects need to be considered for selection of degree of compensation:

- Improvement of Static and Transient stability in normal as well as contingent conditions
- Power flow on the compensated line doesn't increase to the unsatisfactory level
- In case of variable compensation, the range is to be decided in such a way that maximu m limit is effectively utilized to damp out inter-area oscillations

Theoretically, to achieve maximum power transfer through a tr. line, following impedance criteria should be met:

$$Xnet = \sqrt{3} * Res \quad (1)$$

where Xnet & Res are the Line reactance and Resistance respectively.

As per equation (1) above, for a 400kV twin moose conductor bundle line, compensation level to achieve maximum power transfer is limited to 80-85% only, beyond which power transfer capacity would start reducing. However, to provide certain margin, maximum degree of compensation is generally maintained at about 70%. Further, series compensation on lines that are closely connected to thermal generating stations might introduce a negative damping on the mechanical torsional modes in the turbine-generator shaft system. This phenomenon named as Subsynchronous Resonance (SSR) generally occur for high degree of compensation. The resonance frequency is defined by:

$$W_{res} = W_n * \sqrt{(K)} \quad (2)$$

where K is Percentage degree of compensation and W_n is system natural frequency

From the Equation (2) above, it may be seen that for more than 70% compensation, the margin between electrical resonance frequency and network frequency shrinks down and could lead to SSR phenomenon.

A.. Selection of Degree of compensation on 400kV Rourkela-Raipur D/c line - A Case Study

While selecting the series compensation on 400kV Rourkela-Raipur D/c line, extensive studies were carried out to determine the degree of compensation as well as type of compensation, required to enhance power transfer capacity as well as to maintain system stability under all operating conditions. Results for determining the degree of fixed series compensation are indicated below in Table I:

TABLE I
DEGREE OF FIXED SERIES COMPENSATION

Degree of comp.	Base Case		Outage of one circuit	
	Angular Separation (Degree)	Power flow/ckt (MW)	Angular Separation (Degree)	Power flow on healthy ckt (MW)
Nil	26.42	495	46.72	770
30%	20.00	530	36.0	870
40%	17.54	545	30.0	900
50%	15.13	560	28.18	965
60%	12.64	570	23.92	1015

Note: Thermal limit of the line: 1100 MVA

From Table I, it was observed that with 40% fixed Series Compensation, angular separation as well as power flow on the healthy circuit in the East-West Transmission corridor, in the event of outage of one circuit remains within the acceptable range, hence this was found most optimal choice for fixed degree of compensation.

During dynamic conditions, with the increased power flow over the line, during certain contingencies, low frequency(less that 0.8 Hz) inter-area oscillations were observed. Result of the dynamic simulation studies with about 1200MW power flow over Rourkela-Raipur 400kV lines along with following contingency is presented below in Fig. 3.

- Contingency- Single-line-to-ground fault (SLG) for 100 msec at Raipur followed by tripping of faulted ckt.

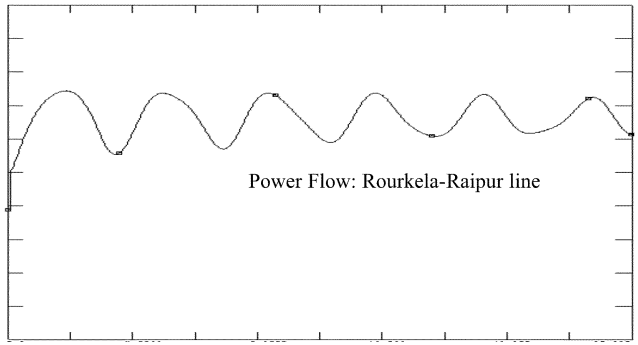

Fig-3: With 40% Fixed Series Compensation

Above cases were repeated with variable compensation in the form of TCSC and result is presented below in Fig. 4.

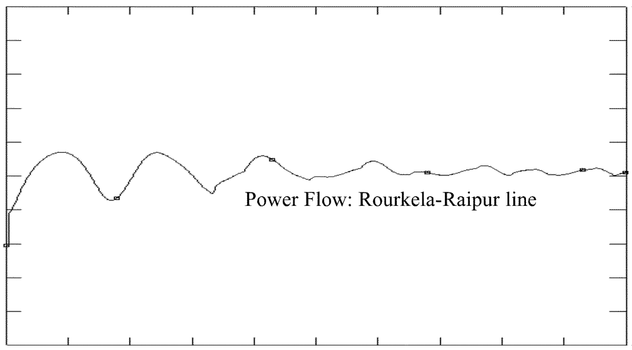

Fig- 4 : With 40% Fixed and 5-15% variable compensation(TCSC)

From the studies, it was observed that to maintain system stability under different network conditions, 5-15% TCSC shall be required (including 3 p.u boost factor) on Rourkela-Raipur 400kV D/c line. Based on the studies, following basic parameters of series capacitor installation were formulated as given below in Table II:

TABLE-II
BASIC PARAMETERS OF SERIES COMPENSATION INSTALLATION

Parameters		Fixed	TCSC
Degree of Compensation	(%)	40	5-15
Series Capacitor reactance	(? /phase)	54.7	6.83
Nominal boost factor	(p.u)	-	1.2
Maximum boost factor	(p.u)	-	3

However, the degree and nature (i.e. Fixed or Variable) of compensation need to be studied on case-to-case basis.

V. COMPONENTS OF SERIES CAPACITOR

Following are the major elements in the Series compensation installation[3]:

- Capacitor bank
- Metal Oxide Varistor (MOV)
- Forced Triggered Spark Gap & Bypass switch
- Current Limiting Damping Reactor & TCR
- Bypass Disconnector & Isolators

A typical Series Capacitor schematic including above elements is shown below in Fig. 5.

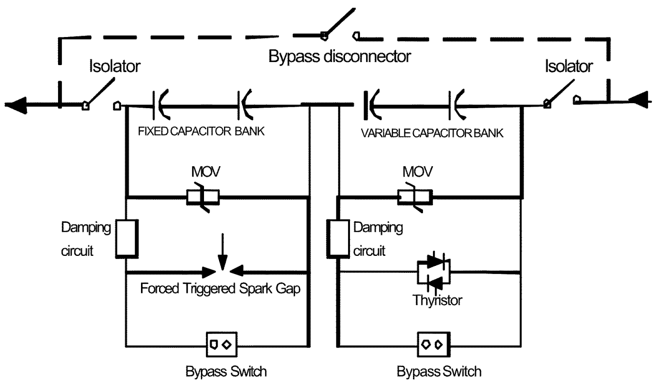

Fig-5: Basic Series Capacitor circuit

VI. SERIES CAPACITOR SCHEME & DESIGN PARAMETERS

The capacitor bank is basically built up of capacitor units connected in Series and Parallel combination to obtain the required sizing (MVAR rating) of the banks. Being series element, the Capacitor bank is exposed to the same current and voltage stress as the transmission circuit itself. Therefore, series capacitor equipment needs to be appropriately designed for these stresses. In addition to protection, it also requires control and supervision facilities to enable it to perform as an integrated part of the power system.

While designing the Series Capacitor, different current stresses due to faults like Internal (i.e. fault within the compensated line) as well as External fault (i.e. fault outside the compensated line) and associated voltage stresses need to be given much emphasis and parameter should be decided judiciously. Various parameters that require special emphasis in design are deliberated in the following sections:

A. Current rating of Series Capacitor

The most important current-stresses of a Series Capacitor in a transmission line are the following:

a) Nominal Current
b) Maximum Continuous Current
c) Overload current (duty cycle-10-30 min & 8 hrs: as per IEC 186)

The current rating of the capacitor bank should not restrict the power flow limit on the line. However, the nominal current rating governs the size of the capacitor bank, hence, the overall cost and functionality of the Series Capacitor tremendously. While making selection of current rating of the bank, there could be two approaches:

- Rating equivalent to thermal rating of transmission line
- Rating equivalent to maximum continuous power flow

However while selecting nominal rated current of the series capacitor, it should be considered that, series capacitor doesn't become a bottleneck with future transmission system expansion. Hence, in first approach, it could be designed on the basis of thermal rating. However, second approach could be adopted after carrying out extensive system studies which would definitely yield some savings in bank rating. In addition, Series Capacitor should also be designed for overload duty cycle as per the IEC standards. Based on the nominal current rating, the capacitor bank size could be calculated as given below:

$$\text{Bank Size(MVAR/ph)}: I^2 * Xc \quad (3)$$

where I is the line current and Xc is the capacitor reactance

For Raipur-Rourkela 400kV D/c line, the nominal current rating was chosen as $1550A_{rms}$ equivalent to thermal rating (i.e.1100MVA) of the line with maximum permissible conductor temperature at 85^0 C. The bank rating for the fixed segment was chosen as 131.45 MVAR/ph and for variable segment it was 19.7 MVAR/ph.

B. Voltage Rating

During fault conditions, substantial transient voltage is developed across Series Capacitors, which could generally exceed the inherent short time voltage capability of a capacitor unit. Design of the capacitor for these high voltage stresses, would result in a completely uneconomical design, hence a separate fast acting over voltage protector across capacitor is preferred which comes into operation to protect capacitor in such situations. To deal with such abnormal system conditions, following equipment are required for protection of Series Capacitor and are described as given below:

1) Over voltage Protection by MOV: The need for a fast acting over voltage protective device with quick reinsertion time is fulfilled by a metal oxide (ZnO) varistor (MOV). The overvoltage protection consists of a bypass ZnO varistor and a forced triggered spark gap connected in parallel with the capacitor segment. Upon fault initiation in the surrounding network, an increased current through the capacitor generates a high voltage across the varistor. Due to non-linear V-I characteristics of MOV, as soon as the voltage crosses protective level, it starts conducting and bypasses excess current thus limiting the voltage across both the varistor and capacitor to the defined protective level, and MOV absorbs additional energy. From system stability point of view, for all types of external faults, MOV should be designed for withstanding such faults, without bypassing the Series Capacitor. Further, MOV is designed for withstanding the maximum fault current due to internal fault through the bank. The bank may be bypassed for any kind of internal faults.

Another important design parameter for the MOV, i.e. Protective voltage level, is decided based on the maximum voltage which can appear across the terminals of the series capacitor during various conditions. Typical criterion for sizing the MOV energy duty is "the bank shall be capable of withstanding a succession of two/three external faults, followed by a severe intemal fault for one second (i.e. dead time) later".

Based on the above, protective level in the range of 2.0 – 2.4 p.u could be selected for the fixed capacitor segment and for variable segment it could be slightly more i.e. upto 2.5 p.u. as TCSC will be subjected to overvoltages when it is damping power oscillations also.

To decide MOV energy rating, extensive transient studies need to be carried out in EMTP where the tr. network is to be simulated as an equivalent system represented by Short circuit capacity, along with the series capacitor and MOV. Total energy capability of MOV is to be considered equal to P*Energy due to external fault + energy due to internal fault (P may be selected as 2 or 3 as mentioned above).

To take care of the harmonic content in the system as well as future expansion of the network and subsequent increase in short circuit level of the nearby system, a margin of +10 to +15% is generally kept in the energy rating of the MOV.

2) Forced Triggered Spark Gap and Bypass Switch: To protect the MOV, a costly element, two different devices are used in parallel to it. The fastest acting device is the forced triggered spark gap and slower acting device is the bypass switch. As soon as energy of MOV is reached to the design level, triggering signal is send to the spark gap as well as to the by-pass switch. The command order for bypassing is decided on the basis of the current and energy setting that in turn is based on the current and MOV energy accumulation at the time of an external fault. Spark Gap with minimum operation time of few ms is available, which helps in reducing the MOV energy requirement. In TCSC segment, forced triggered spark gap is not required because thyristor valve takes care of fast bypass and reinsertion during system disturbance and recovery conditions respectively.

Bypass switch is basically a slow acting device, which is operated subsequent to the Spark gap triggering to bypass the MOV. The bypass switch normally remains in the open condition and designed for the nominal current. It is installed in parallel with MOV and spark gap, and thus the voltage between the terminals is limited to the protective level of MOV, which is the maximum recovery voltage for the switch. The maximum making current is derived from the damping equipment and MOV studies which also gives the withstand voltages for the bypass switch. The transient recovery voltage is applicable during opening of the bypass switch.

3) Current Limiting Damping Reactor(CLDR): The damping reactor is basically put in series with the Spark Gap, to limit the Capacitor discharge current amplitude and damp out the oscillations generated by the spark gap operation or by-pass switch closing. The inductance value is chosen to avoid parallel harmonic resonance between the capacitor and bypass circuit. A damping resistor is also provided with the CLDR in order to provide the required capacitor discharge damping ratio between consecutive cycles.

The current limiting damping reactor (CLDR) is designed on the basis of following aspects:

- Crest value of the discharge current not to exceed 100 times the rated capacitor current for the sustained arc gaps and to damp out discharge current oscillations.
- Discharge frequency shall not coincide, as far as possible, with harmonics of the following order :Hn = 3 * k (where k=1,3,5..) & Hm= 6 * n$\pm$1 (where n=1,2,3..)
- Product of the discharge current amplitude and the discharge frequency shall not exceed 100kA kHz.,which is the requirement of bypass switch.

4) Bypass Disconnector and Isolators: The Bypass disconnector and Isolators are basically provided to bypass the entire Series Capacitor installation in case of requirement of isolation of Capacitor banks during line energisation, maintenance and repair works etc.

5) Thyristor Controlled Reactor (TCR): TCR, a reactor connected in series with anti-parallel thyristors, is an integral part of TCSC to achieve desired boost level for control purpose. However, the reactors have to conduct a large current during operation with high boost factor and are therefore relatively big. The reactor is selected in such a way so that parallel resonance between the capacitor and the bypass circuit is avoided and low loss.

VII. POWER OSCILLATIONS DAMPING CONTROLLER OF TCSC

Damping controller is the brain of TCSC used for damping of electromechanical power oscillations in the transmission line through modulation of the reference signal for TCSC apparent reactance at main frequency. Switching between several different operating modes (at least the capacitive boost mode and the bypass mode) also may be used to contribute to damping at large-signal disturbance[4]. The damping controller provides the reference for the operating mode and the reference for reactance deviation from the steady-state value. The input signal to the Power oscillation damping controller is active power in the transmission line.

VIII. PLACEMENT OF SERIES COMPENSATION EQUIPMENT

As the series capacitor is placed in series with the line, entire installation requires same insulation level as that of transmission line. For this, the installation is placed on insulated platform with same insulation parameters-LIWL, SIWL etc.

Location of Series Capacitor on the line mainly depends upon the economic consideration. Installation of Series Capacitor at the middle of the line is technically most suitable, however, it requires additional cost for establishment of a separate substation, O&M expenses etc, Hence, it does not become an economical option. However, in most of the applications, the capacitor bank is placed at the receiving end substation terminal as no additional infrastructure/O&M facilities are required without scarifying any technicality.

Further, in case of placement of capacitor at the substation for long lines with shunt reactive compensation, to avoid loop forming between Series Capacitor, Shunt reactor/part of line/fault and arcing, it is preferable to place Series capacitor towards bus side of the line.

IX. Issue in Series Capacitor Installation

Issue which needs to be addressed while implementing Series compensation on EHV transmission line are discussed in the following paragraphs:

A. Distance Protection Schemes

Integration of series capacitor into the line makes the line protection complex due to abrupt change in line series impedance, which changes the fault current, voltage and apparent impedance seen by the relays depending upon the location of fault. In addition, fault current may change from its normal lagging angle, with respect to voltage, to a leading angle. Hence, presence of series capacitor on a line can cause maloperation of the relays on the compensated line as well as on the adjacent lines. Following factors affects the operation of relays due to series compensation:

- Degree of compensation
- Location of fault
- Pre-fault condition
- Short circuit strength of particular bus

Hence for a particular fault, the inputs to the relay get affected by the series capacitor if the location of Series capacitors is between the relay measurement point and the fault point. Therefore, before installing Series Compensation, nearby relay protection schemes need to be reviewed and suitable action need to be taken regarding:

- Resetting of relay parameters e.g. Zone settings etc.
- Installation of latest State-of-the-Art numerical distance relays compatible with Series Compensation schemes.

In case of 400kV Rourkela-Raipur D/c line, studies were carried out in EMTP[5] representing the compensated line and adjacent transmission network one bus away and simulated both SLG and 3-phase faults (internal & external). The variation in impedance were measured and tested through Relay testing kits to examine the effect of proposed Series Compensation. In case of abnormality, the relays are required to be replaced suitably.

X. Conclusion

Series compensation is a tool for utilization of existing transmission infrastructure optimally. The Series capacitor, compensate the inductive reactance of transmission line, thereby making virtual reduction in line length and enhances the power transfer capacity. The size of the series capacitor, hence its cost basically depends upon the rated current, which is determined after carrying out studies under various network conditions. Being series element, adequate protection is required which is achieved by installation of ZnO varistor (MOV), forced trigger spark gap and bypass switch. Rating of these protective devices are decided based on the EMTP studies by simulating external and internal fault as well as other conditions. Besides, for variable series compensation (TCSC), thyristor controlled reactor (TCR) is also required to provide necessary capacitive boost for control purpose. Further, to damp out the low frequency inter-area oscillations, Power Oscillation Damper (POD) is required whose basic principal of operation is highlighted.

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