# Review of Series Compensation

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***Abstract****- The High Priority Incremental Load Study (HPILS) was initiated in 2013 to develop a long range plan that identified system reinforcements required in the Southwest Power Pool (SPP) footprint in order to accommodate the unprecedented load growth that had not been identified by previous planning studies. This rapid expansion of load was brought about by an increase in the development of oil and gas fields, the firming of previously interruptible loads and an increase in the forecast expansion of major industrial loads.*

*As part of the HPILS process, initial screening of options by SPP staff suggested that 50% series compensation (SC) should be considered on the existing Tolk - Eddy Country 345kV line as part of a potential EHV solution set to address the reliability needs associated with large load additions in southeast New Mexico and west Texas. Due to the fact that the proposed solution would introduce the first series compensated line in the SPP footprint, significant concerns and uncertainties were expressed about the merits and implications of adding SC to existing or planned EHV lines in SPP.*

*Series compensation has been in use in electrical networks worldwide since the 1950s. It is a tried and true technology that continues to grow in popularity as an effective means of resolving a number of network issues such as:*

*Improving transient system performance of the system following system disturbances by reducing rotor angle difference between generators;*

*Compensating for reactive power losses in transmission lines to better regulate system voltages;*

*Modifying and improving the balance of power flows between adjacent transmission corridors by changing impedances, similar in effect to phase-shifting transformers and HVDC;*

*Damping of system oscillations when used with actively controlled Thyristor Controlled Series Capacitors (see Section 2.3); and*

*Mitigating geomagnetic induced currents by blocking low frequency current flow.*

*The first two points are further discussed in Sections 2.1.1 and 2.1.2 whereas the remainder are beyond the scope of this paper.*

*By addressing the above issues with less capital intensive solutions such as series compensation, the capacity of existing transmission lines can be increased thereby allowing for the deferral of major transmission line investments and the optimization of total build out. This permits better management of risk through the preservation of right of ways and corridors for future needs using an option that requires minimal permitting and siting requirements. Overall asset utilization increases and losses are lowered. Series compensation improves system reliability while minimizing the impact on rate payers.*

*The various sub synchronous interactions between the network and the series capacitor are well known phenomena and there are a variety of ways available to counter-act them. The literature on the topic is extensive and the techniques are well documented and their relative merits are discussed at lengt*

*This document seeks to provide a better understanding of the implications of adding series compensation technology to the SPP network. The current status of the technology is reviewed and recent advances in the techniques that deal with known issues that affect the network are explored.*

## I. INTRODUCTION

### General Review

A general review of the applicability of series compensation shows that it serves to increase power transfer under steady state and transient conditions, as well as regulating voltage variations. A series compensation installation can be ‘Fixed’, ‘Thyristor Controlled’, or a combination of both.

### 2.1.1 Reducing Rotor Angle Separation

The classic power transfer equation, adapted to take account of the series capacitance, XC, shows that as the level of compensation, K, increases, the power transfer increases for a given angle δ. This is because capacitive impedance is negative with respect to an inductance thereby reducing the overall impedance of the line. The equation and a simplified network representation are shown in Figure 2-1 for illustrative purposes.

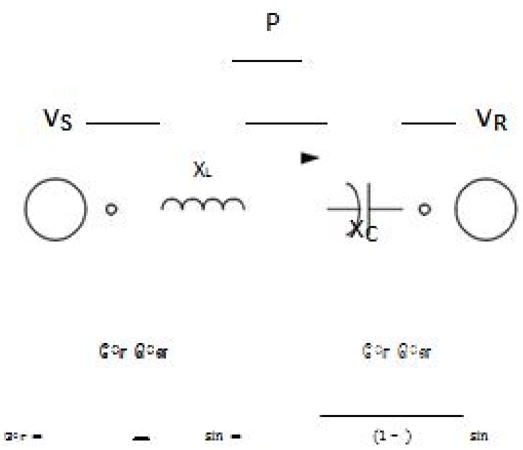

Figure 2-1 - Power transfer equation

From this, we see that when there are no changes to system impedance, the maximum power that can be transferred occurs when the phase angle between the two ends reaches 90o as demonstrated in Figure 2-2.

P ▲ PMAX

(K = 50%)

$$P = \frac{V_R V_S}{X_L (1-K)} \sin(\delta)$$

PMAX

(K = 0%)

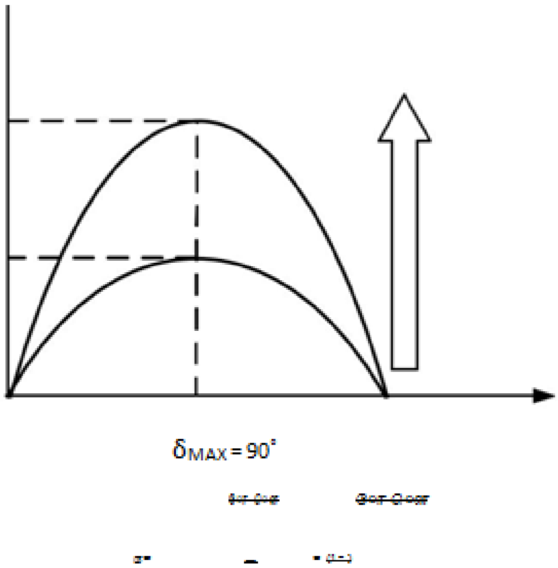

Figure 2-2 - Pmax with all lines in

The effect of adding series compensation is shown in Figure 2-2 where for a same angle δMAX, the theoretical maximum power transfer, PMAX, doubles when compensation level, K, reaches 50%. Analogously, for a given power flow (say PMAX when K=0%), rotor angle separation goes from 90o with no compensation to a much smaller value when compensation is increased.

As faults occur and branch elements are switched out of service, the resulting changes in network impedance cause imbalances between the electrical and mechanical torques at play in the generator and an oscillatory behavior, best characterized by the swing

equation: 2 ଶଖ =–

where H is generator inertia, ωs = 2 π fs is synchronous angular speed, Pmec is the mechanical power generated by the turbine, Pelec is the electrical power generated by the alternator that responds to the system demand. During steady state, when the system frequency is at its nominal 60 Hz, both the mechanical and electrical power are equal and the machine continues to spin at synchronous speeds.

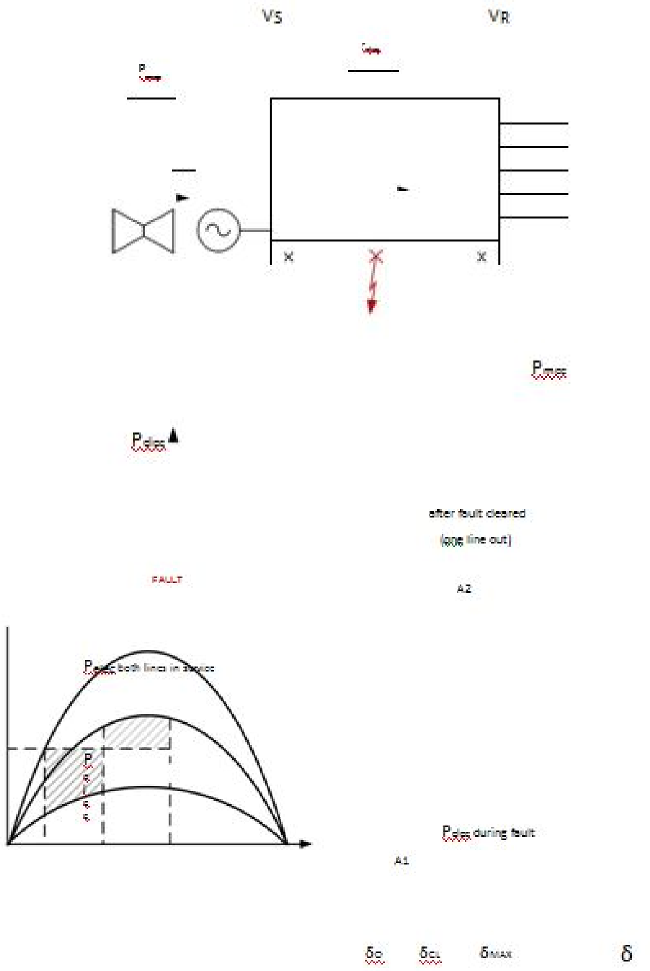

Figure 2-3 - Equal Area Criterion for a simple system

Prior to fault inception, the generator in Figure 2-3 has angle δo and is generating Pmec on the Pelec curve with both lines in service. At the instant of the fault, the impedance seen by the generator reduces and very little active power is generated due to the fault being situated between the load and the generator. The generator's operating point is now where δo crosses the curve of P during the fault. Mechanical power from the turbine remains constant1 and the sudden drop in electrical power results in an imbalance causing the rotor to speed up. The angle between rotor field and network field increases and the generator's operating point moves along P for the duration of the fault until the angle reaches δCL at which time the line's protective relays clear the fault by disconnecting the line. Once the fault has been cleared, the generator changes its operating point by moving up to the graph of P after the fault is cleared. Since the impedance of the single line is double the impedance of the two lines in parallel, this curve has a smaller amplitude than the initial but greater than during the fault. Electrical power is now greater than mechanical power produced by the turbine and the rotor begins to decelerate until eventually coming to rest where the electrical power is equal to the mechanical power of the turbine.

The area identified as A1 in Figure 2-3 corresponds to the acceleration energy absorbed by the rotor during the fault. The area A2 corresponds to the decelerating energy that the rotor can return to the network to return to a stable operating point.

The Equal Area Criterion states that the generator will return to a stable operating point if A2 ≥ A1. This is equivalent to saying that the decelerating energy available to the rotor is at least equal to the accelerating energy absorbed during the fault.

The relative sizes of A1 and A2 are determined by:

The initial phase angle, δo ;

The protection clearing time that determines δCL ; and

The before and after impedances that determine the amplitude of the power relationship.

### 2.1.2 Voltage Regulation

Voltage stability is improved due to the self-regulation characteristic of series capacitors. Contrary to shunt devices where reactive output is a function of the inverse square of the voltage change, the reactive power output of series elements increases with the square of the current. As transfer increases across a transmission line, reactive losses caused by the inductive nature or transmission lines are partially offset by the increase in reactive power generated by the capacitor. Consider Figure 2-4, the reactive power balance for a 500 kV line of 300 miles in length.

The maximum power transfer is increased for the series compensated line due to the increased availability of reactive power to support local voltage as flow increases. Self-regulation also means that lines subject to sudden load variations due to nearby loads or generators switching on or off will have better regulation2.

[1] In the time frames where protective devices operate (~ 50 – 200 ms), governor action is negligible and the turbine output can be said to remain constant.

[2] Voltage regulation of a line generally refers to the tendency of the voltage at the receiving end to vary for given changes in flow.

Review of Series Compensation for Transmission Lines

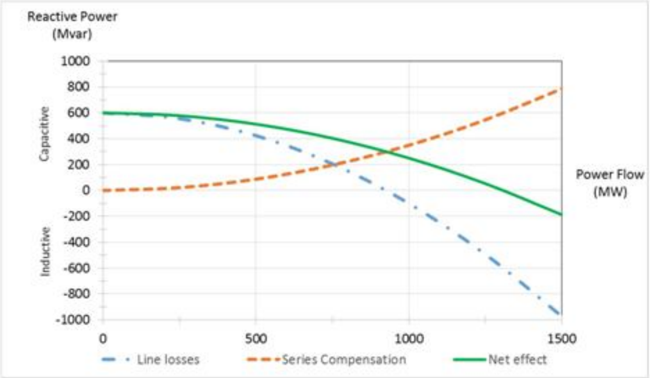

Figure 2-4 - Self-regulation of series compensation – 500 kV line, 300 miles long

As compensation levels, K, increase the reactive output of the series capacitor increases and the voltage regulation across the line is improved as shown in Figure 2-5.

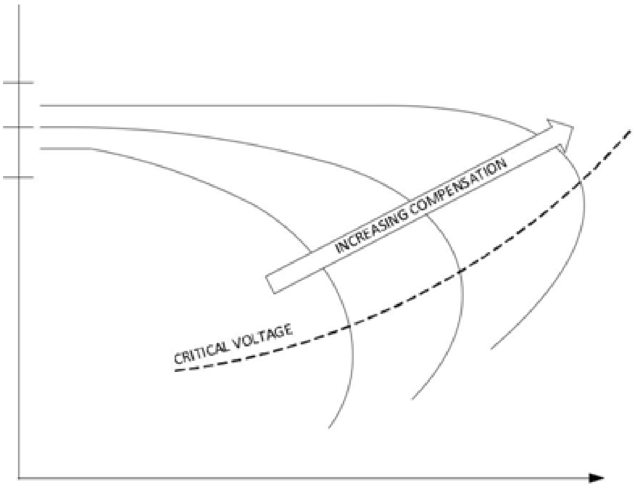

Figure 2-5 – Effect of increasing compensation levels – 500 kV line, 300 miles long

The range of power transfer for which the voltage stays within the normal range increases as the level of compensation increases. It must be noted that the Critical Voltage, the point at which voltage will collapse for any increase in transfer, also increases considerably as compensation levels increases. Post contingent voltages in compensated systems must be verified to ensure that a voltage collapse scenario has not been introduced along with the series compensation. This is particularly true for situations where unplanned outages result in unusually high flows across compensated lines.

## 2.2 Fixed Series Compensation (FSC)

A fixed series compensation installation consists of a parallel combination of capacitors, over-voltage protection, and a bypass breaker, which are all installed on an elevated platform insulated to the line voltage. The FSC main circuit components are shown in Figure 2-6. The capacitor bank is usually rated to line currents associated with normal peak power flow and power swing conditions. Rating the capacitor banks to current and voltage levels associated with fault conditions is generally not considered economical and over voltage protection is provided to limit the voltage across the capacitor during fault conditions. The over voltage protection typically consists of two parts:

A zinc oxide varistor (MOV) with highly non-linear characteristics that conducts negligible current during normal operation and conducts freely once the voltage across it reaches the protection level thereby bypassing the capacitor bank. The MOV is built up of individual MOV blocks placed in series to obtain the desired voltage protection level and in parallel to be to absorb the desired energy during faults. If the fault is cleared without the ratings of the MOV being exceeded, the MOV will stop conducting once the voltage across it drops below the protection level and the capacitor will return to normal operating conditions.

A fast protective device (FPD) that can be triggered for certain fault conditions such as faults on compensated line segments or for extreme faults when the energy absorbed by the MOV exceeds rated values. Fast protective devices have typically consisted of triggered air gaps although new technologies are being introduced that use arc-plasma injectors in parallel with a fast contact to avoid the difficulty of correctly distancing and maintaining the electrodes in the air gap.

The bypass breaker is normally in the open position and can be used to switch the series capacitor in or out during planned operations. It also serves to bypass the series capacitor, MOV and FPD if the fault is not cleared within a pre-determined time. It must be able to carry the rated MOV voltage as well as the maximum capacitor discharge current. Bypass breakers are specially designed and rated to withstand the higher transient frequency and interrupting currents when bypassing a series capacitor. Bypass breakers are normally SF6 puffer type with controls at ground level.

A damping circuit - usually an air core reactor - is placed in series with the FPD and the by-pass breaker to limit and dampen capacitor discharge currents when the FPD triggers or the bypass breaker is

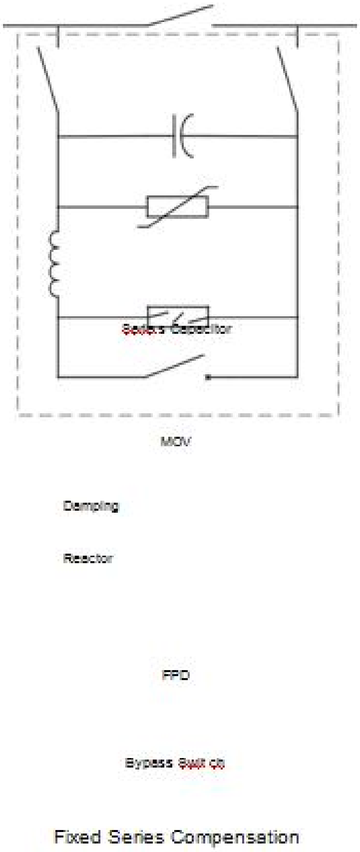

Figure 2-6 - FSC main circuit components

2.3 Thyristor Controlled Series Compensation (TCSC)

A thyristor controlled series compensation installation typically consists of two modules connected in series:

A fixed series compensation module (as described above), and A module consisting of a series capacitor in parallel with a thyristor controlled, air-core reactor.

As with the FSC, the TCSC is platform mounted and insulated at line voltage. A TCSC installation can be green field or thyristors can be added to control part or all of an existing FSC installation [2].

When the thyristor gate is blocked, full current flows through the capacitance and the line is fully compensated. When the thyristor gate is fully conducting, the capacitor is effectively bypassed. If the valves are gated for partial conductance, it is possible to smoothly vary the impedance of the TCSC.

Over-voltage protection is assured by the connection of an MOV across the capacitor. A bypass breaker or disconnect is generally included to allow for maintenance and better over-voltage protection.

Depending on the network requirements TCSC installations may be 100% variable although most typically have a fixed level of compensation combined with a variable level of compensation as shown in Figure 2-7. This allows the cost to be optimized by only controlling the series capacitance that provides reliability or other benefits. The controlled part can be scaled .

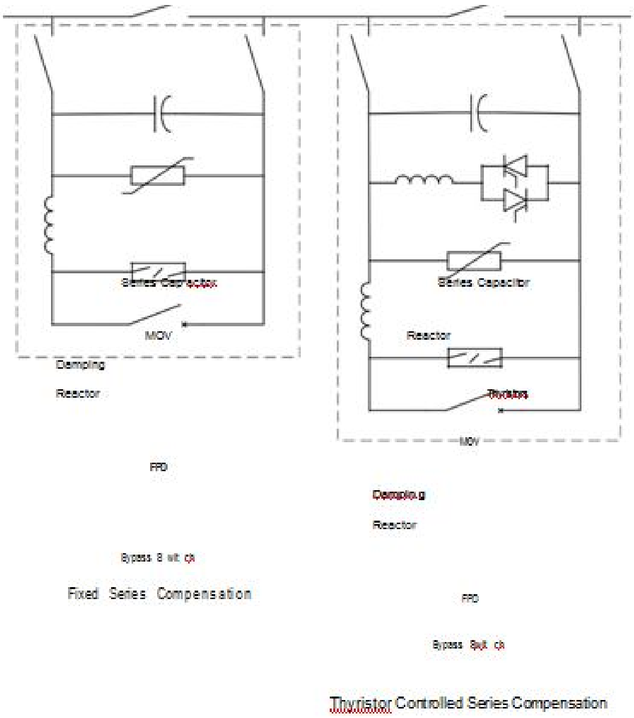

Figure 2-7 - TCSC primary circuit components

## II. CONCLUSION

In this paper,the problem of review of series comoensation is comprehensively Analyzed.And the conclusions are as follows:

1. To obtain the best technical and economic advantages,we should select appropriate Intstalling location and capacity of series capacitor.

2. Fixed series compensation is self-adaptive to load change and has a compensation Effect to heavy load line,but light load line with high load fluctuation may cause Abnormal voltage rise in front the compensation point,that needs setting reasonable Rules to switch series capacitor.
3. Since loads vary wildly during day and night,and some loads may be very smallAt night,estimated method for position and capacity of series capacitor is advisableAnd practical.

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