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A COMPARISON ON PERFORMANCE OF TCSC/SSSC FOR A RADIAL SYSTEM

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ABSTRACT

Power flow control in electric power networks is becoming one of the crucial factors of electric power system development. Because of growing energy demand, optimization of power systems operation and deregulation the power transmission inside is expected to increase in the future. In many countries, the environmental problems and increase in public opposition place restrictions on building of new transmission lines. The consequence may be the need for more efficient use of the existing transmission facilities, in certain situations beyond the limits considered in the original planning phase. In such a situation the need for effective dynamic power flow control is evident. The solution might be FACTS (Flexible AC Transmission System) technology based on power electronic equipment. As one of the most attractive FACTS technologies, TCSC (Thyristor Controlled series Capacitor) has won wide attention in the world. Static Synchronous Series Compensator (SSSC) is another device for variable series compensation of transmission lines.

This paper deals with comparative study of performance of TCSC and SSSC for a long radial transmission line connecting a generator source to big load centre. Appropriate shunt compensation also designed for the system. Since a major concern in such system is regulation of the load point voltage, TCSC/SSSC along with shunt compensating devices, has been designed to aid in regulating this voltage. Detailed simulation using PSCAD/EMTDC software has been done to assess efficacy of the design.

KEYWORDS: Radial System

INTRODUCTION

In a power system, ideally, bus voltage should be kept constant. But bus voltage magnitudes vary with the magnitude of the load. The amount of variation depends upon system characteristics as well as nature and variation of loads. Compensation essentially involves provision of sources and sinks of reactive power and their management to improve the quality of supply in power systems. The main objective of load compensation is power factor correction, improvement of voltage regulation and load balancing. Power factor correction is generally done at the load points. It compensates for the reactive power requirement of loads. Through this we can avoid the unnecessary reactive currents in the transmission lines.

Voltage regulation is an important issue with loads which vary their demand for reactive power. In most of the industrial loads power factor is lagging. Variation of these loads causes a wide range of reactive power flow variation in the transmission system.

Voltage at the consumer point should usually be within the range of $1\pm.05$ times the nominal voltage. Compensating device has a vital role to play in maintaining supply voltages within the specified limits. Other important factors are load balancing and elimination of harmonics. The unbalanced load gives rise to negative and zero sequence components in voltage and currents. These components will cause additional loss in machines, increased ripple in rectifiers, malfunction of several type of equipment, saturation of transformers and excessive neutral currents. Harmonic current can cause excessive heating in transformers and machines also. Adequate filtering circuits are necessary to eliminate the harmonics.

In addition to compensation at load point, it is necessary to have compensation of transmission lines, especially if they are more than about 300 km in length. This compensation in general, is series capacitance compensation supported by appropriate shunt compensation. Proper line compensation increases the maximum power transfer capability of the line, giving a satisfactory voltage profile of the line under various condition of operation and relieves the generator from the task of supplying the reactive power needs of the line. Furthermore, in power systems, at selected high and extra high voltage buses, it may be necessary to have static and dynamic voltage support equipment

In EHV transmission system, the capacitive generation of the line poses problems during line charging, operation at low loads and switching operations causing an undesirable voltage rise on the line. Variable series compensation methods can effectively mitigate the above problems and can enhance their power transfer capability.

Thyristor Controlled Series Compensator scheme was proposed by Vithayathil [1] as a method for rapid adjustment of system series reactance. N. Christl et al. [2] presents the steady state and transient characteristics of the Thyristor Controlled Series Compensator and their impact upon design and operation. The capacitive reactance is determined by the desired steady state and transient power transfer characteristic as well as by the location of the capacitor on the line. The effectiveness of the controls for different purpose depends on the location of control device. There are studies which allocate FACTS devices for damping inter-area oscillations and stability enhancement, by employing eigen value analysis.

TCSC be used to enhance the voltage stability, since the inserted series capacitor affects the reactive power distribution in the interconnected power systems. The voltage source converter based series compensator, called Static Synchronous Series Compensator, proposed by Gyugyi [3], is within the concept of using converter-based technology uniformly for shunt and series compensation, as well as for transmission angle control. An SSSC can be operated in different modes, depending on whether or not the device is stand alone or part of a UPFC. Sen [4] has developed an EMTP simulation model of a stand-alone SSSC based on a lwo-1evel, 24-pulse harmonic neutralized voltage source inverter and used this model to study the dynamic performance of this SSSC. Sen has also developed an EMTP model of an SSSC based on three level 24-pulsed inverter. In both the aforementioned SSSC models, the discontinuous nature of the multipurpose inverters' ac output waveforms and the SSSC controls are represented in detail.

Wang [5] investigates the damping control of a static synchronous series compensator installed in power systems. The linearized model of the SSSC integrated into power systems is established and methods to design the SSSC damping controller are proposed. In this paper both cases of single machine infinite bus and multi machine power systems are studied and example power systems are presented. The difference between controllable series compensation and Static Synchronous Series Compensation regarding power oscillation damping effectiveness is also demonstrated here. Gyugyi et. al. [6] describes an active approach to series line compensation, in which a synchronous voltage source, implemented by a GTO based voltage-sourced inverter, is used to provide controllable compensation. This paper also discusses the basic operating and performance characteristics of the SSSC, and compares them to those characterizing the more conventional compensators based on thyristor-switched or controlled series capacitors. Sood [7] presents a short tutorial on an SSSC application using an EMTDC based model. A single phase model is presented and explains the fundamental principle involved. Ref [8] focuses on comparing the steady state characteristics of the SSSC with and without Energy Storage System (ESS). The SSSC output voltage range, compensated output power, operating modes and its effects on transmission line power flow control are extensively discussed using characteristic curves. Based on these curves, a new generalized PQ decoupled control concept is proposed for an SSSC with a Battery Energy Storage System (BESS). The control interaction study is carried out through eigen value analysis and time domain simulations.

VARIABLE SERIES COMPENSATION

In order to maintain constant voltage profile along the transmission line, the shunt compensation is very much effective. Moreover, the enhancement of power flow is possible by increasing the angle between the sending end and receiving end voltage. But the control of power is possible only with Variable series compensation. Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator(SSSC) are the most effective FACTS device to control power flow in transmission lines.

Variable series compensation can be applied to achieve full utilization of transmission assets by controlling the power flow in the lines, preventing loop flows, minimizing the effect of system disturbances, reducing traditional stability margin requirements and improve voltage stability.

The basic operating principles of the TCSC and SSSC can be explained with reference to the conventional series capacitive compensation of Fig 1 and Fig 2.

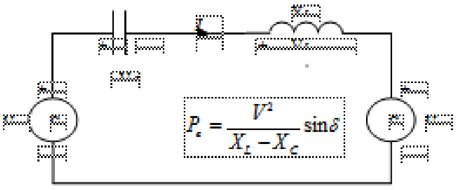

Figure 1: Conventional Series Compensation

The phasor diagram clearly shows that at a given line current the voltage across the series capacitor forces the opposite polarity voltage across the series line reactance to increase by the magnitude of capacitor voltage. Thus, the series capacitive compensation works by increasing the voltage across the impedance of the line, which in turn increases the corresponding line current and transmitted power. It follows therefore that the same steady state power can be transferred if the compensation is provided by a synchronous AC voltage whose output precisely matches the voltage of the series capacitor.

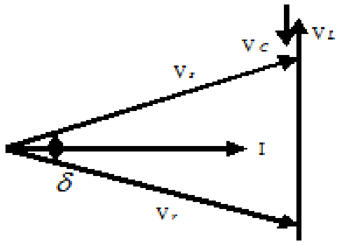

Figure 2: Vector Diagram

The capacitor is reactive impedance in series with the line. Therefore the voltage across it is proportional to the line current which is a function of transmission angle. With change in transmission angle (and line current) the compensating voltage also changes. The transmitted power P_k can be expressed as a function of the degree of series compensation (k_{se}). ie,

$$P_k = \frac{V^2}{X_L(1-k_{se})}\sin\delta$$

Where,

$$V_s = |V|\angle\delta_1 , V_r = |V|\angle\delta_2 \text{ and } \delta = \delta_1 - \delta_2 \quad \text{ and } k_{se} = X_c / X_L$$

Static Synchronous Series Compensator (SSSC)

The SSSC injects the compensating voltage in series with the line irrespective of the line current. The transmitted power P_e therefore becomes a function of the injected voltage $\overline{V}_q$.

A generalized expression for $\overline{V}_q$ can be written as

$$\overline{V}_q = \pm jV_q \frac{\overline{I}}{I}$$

Where, $\overline{V}_q$ is the magnitude of the injected compensating voltage

The transmitted power P_e can be expressed as

$$P_e = \frac{V^2}{X_L}\sin\delta + \frac{V}{X}V_q \cos\delta/2$$

The normalized power versus angle δ plots are shown in Fig 2.6 for five values of $\overline{V}_q$ (0,± 0.353, ±0.707). Comparison of Fig 2.5 and Fig 2.6 clearly shows that whereas the series capacitor increases the transmitted power by a fixed percentage of that transmitted by the uncompensated line at a given δ, the SSSC increases it by a fixed fraction of the maximum power transmittable by the uncompensated line, independently of δ, in the important angle range of $0 \le \delta \le 90^0$. The series capacitor can only increase the transmittable power, where as the SSSC can increase as well as decrease it, by reversing the polarity of the injected voltage. Furthermore, if this (reverse polarity) injected voltage is made larger than the voltage impressed across the uncompensated line by the sending end and receiving end systems, that is, if $\left|\overline{V}_q\right| > \left|\overline{V}_s - \overline{V}_r\right| \quad (\left|\overline{V}_q\right| = \left|\overline{V}_s - \overline{V}_r\right| + IX_L)$,. then the power flow will reverse.

Thyristor Controlled Series Compensator

It consists of capacitor connected in parallel with a fixed reactor of inductance L and a bidirectional thyristor valve. In practical case there are many thyristors connected in series to meet the required blocking voltage levels at a given power rating. As the susceptance is varied by varying the firing angle, the current through the inductance varies and hence the current through the capacitor. This means that this

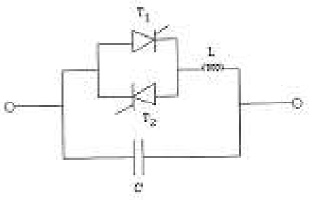

Figure 3: Single Module of TCSC

Scheme provides a continuously varying capacitor. TCSC have three basic modes of operation, thyristor blocked (zero thyristor current), capacitor “bypassed” (full thyristor current) and vernier (partial thyristor conduction) mode of operation. In capacitive vernier operation the current through the capacitor will dominate over the current through the inductor, giving a net capacitive reactance to the parallel combination. In inductive vernier operation, the opposite situation obtains, that is, the current through the inductor dominates over the current through the capacitor, giving a net inductive reactance to the parallel combination. The basic equation of TCSC Fundamental Impedance is

$$Z_{TCSC} = R_{TCSC} + \mathrm{j}\, X_{TCSC} = \frac{V_{TCSC}}{I_{LINE}} = \frac{-jXcI_{cap}}{I_{line}}$$

The cost of a given compensator scheme is often the main factor determining its practical application. The most significant indicator for the ultimate cost effectiveness of a compensator is the ratio of the maximum range of attainable VAR output to the VA rating of the equipment. This ratio is clearly impressively high for the SSSC. For a realistic assessment of relative costs, both the necessary VA ratings and at least the major difference in hardware has to be considered.

Apart from the power semi-conductors (GTO *Vs* conventional thyristors), the greatest difference from the standpoint of cost is in the auxiliary power components and installation structure. The TCSC is coupled directly to the transmission line and therefore working on a high voltage platform. The installation involves considerable on-site labor. The equipment is not visually observable in operation and its maintenance and servicing are relatively cumbersome. But the SSSC installation is on low voltage platform and involves less labour cost.

STUDY SYSTEM

The study system consisting of a 400 miles long radial line connected to the load through a TCSC. The location of TCSC is 150 miles from the sending end .The normal voltage of the line is 500kV. Proper fixed reactive shunt compensation will give satisfactory voltage profile of the line over a wide range of operating condition if the line is operated as a symmetric line, Miller [5]. In the present case, the line is radial and the load end voltage needs to be regulated. In order to obtain satisfactory line voltage profile and reasonably regulated receiving end voltage over a wide range of power flow, switched shunt compensation is used. In any case, design of appropriate compensation needs detailed simulation of the line under varies condition of operation, that is, over a reasonable range of power factor and degree of series compensation This study has been undertaken here with view to design appropriate shunt compensation

Figure 4. shows a circuit schematic of study system. The two section of the transmission line on either side of TCSC/SSSC are represented by their π equivalent circuits. The line capacitance is compensated by shunt reactor. For the sending end 150 miles length, the shunt reactor L_1 and L_2 fully compensate for the line capacitance of this section. However in order to prevent the sagging of voltage at receiving end under heavy load, it is decided not to fully compensate for line capacitance in this section. Reactance should be such that, on light load, the voltage profile of the section would be satisfactory, Furthermore, as load increase, there comes a point where, in order to prevent voltage at receiving end going down beyond permissible limits, it become necessary to give voltage support using shunt capacitance. One switched shunt capacitor is provided at the receiving end.

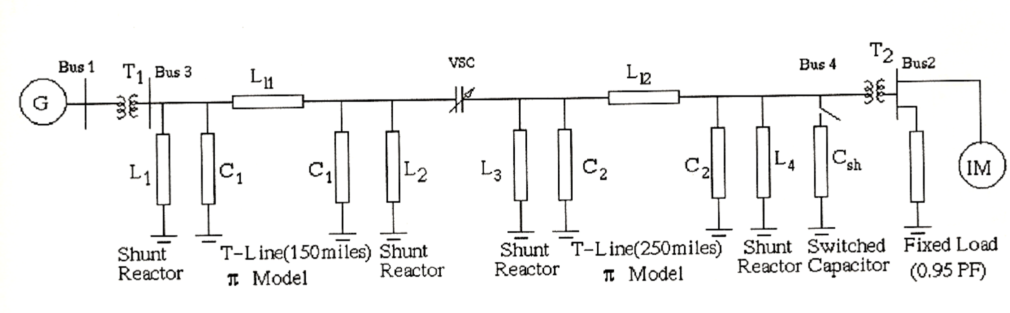

Figure 4: (Study System)

Design of Shunt Compensation

Design essentially utilizes result of voltage profile on the line for various load of fixed power factor and for various degree of fixed series and shunt compensation. The load power factor considered is 0.90 lag

In the analysis, the behavior of the transmission system with the same degree of compensation of 0.2 means that each of the shunt reactor $L1, L2, L3, L4$ in Fig 4 compensates for 20 % of the line capacitance in the π representation it is in parallel with. The analysis is done by assuming constant sending end voltage and fixed load power factor value sending end voltage is $1.0\angle 0$ pu. B_{c1} B_{c2} are the shunt suceptance of the π section 1 and 2 respectively X_1, X_2, X_3, X_4 are the shunt compensating reactance *and* X_{11}, X_{12} are the series reactance of the two π section X_{se} the capacitive reactance of the variable series compensator.

The equation for solving for the system voltage and currents for given load active and reactive power is given below

$$I_2 = \frac{E_S Z_{12}}{(Z_{12}^2 - Z_{11} j(X_{b2} + X_\beta + X_X))|I|^2 - Z_{11}(P + jQ)}$$

Figure 5 shows the variation of receiving end voltage with real power without series compensation, for different degree of shunt compensation. When there is no shunt compensation the no load voltage is about 1.45 pu, for the best operation of the equipments, the voltage at the receiving end should be keep within the range of 1 ± 0.05 pu .When the line is 100% shunt compensated the maximum power capability reduce to 0.20 pu within the allowable voltage. It is to be noted that normally power system operates in lagging load condition

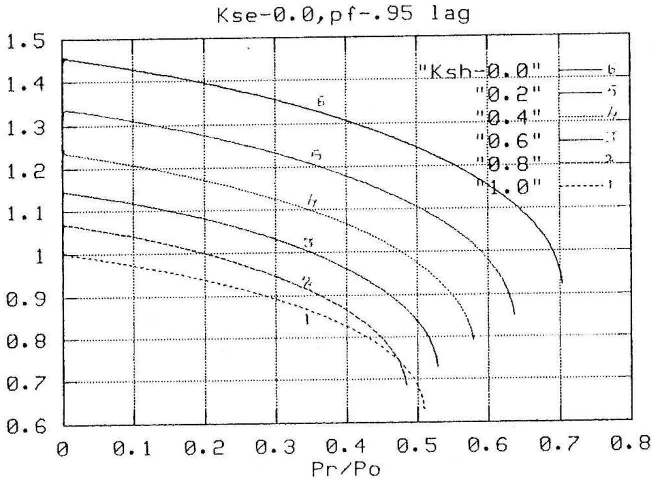

Figure 5

The shunt capacitors C_{sh} provided at receiving end will be switched on when the receiving end voltage goes down to 0.95 Pu. The value of C_{sh} chosen is 90% of the line charging capacitance of this section.

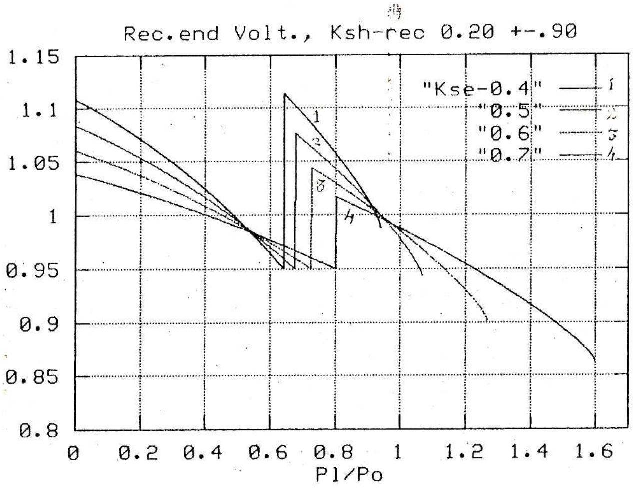

Figure 6

Figure 6 shows the receiving end voltage variation with real power for series compensation 40%, 50%, 60%, and 70%. Note that the above analysis has not taken into account the reactance of line transformers. It is expected that with transforms, the maximum power capability of the line would be less than based on the above analysis.

MODELING FOR EMTDC/PSCAD SIMULATION & CONTROL STRATEGIES

Modeling of System

As mentioned earlier, the study system is a single machine load bus (SMLB) system. The 150 miles section is fully compensated for line charging capacitance using shunt reactor. In the second section 80% line charging capacitance at the TCSC side and 20% at the receiving end are compensated by fixed reactance. An additional switchable capacitance of value 90% of the line charging capacitance of the second section is provided at the receiving end .The capacitor will be switched on when the voltage at the receiving end falls to 0.95 pu and removed when voltage rises upto 1.05 pu.

The generator is modeled as a seventh order model. Saturation in the generator is neglected.

As the study system is a radial one, the governor should be properly modeled to take care of the variation of the load .The model chosen is the hydro governor model HGOV18 (IEEE 4pc2). The exciter model by a PSCAD model (EXCI 35). Transformers are modeled with two windings. The transformer at the sending end is rated 1000 MVA, 22/500 and at the receiving end is rated 1000 MVA, 500/13.8 kV. The no load loses and saturation are neglected.

The transmission line is modeled as two π equivalent circuits for length of 150 miles and 250 miles .the line is considered to be a single circuit line. Two kinds of loads are modeled .One is fixed load consisting of a resistance in parallel with an inductance and other is an induction motor

TCSC Controls

The firing control of TCSC is synchronized with the current. The firing scheme used is IPC (individual phase control). This is for the firing of forward looking Thyristor of one phase. The pulse width in the case is kept at 20^o

Main Control of TCSC

The main control of the TCSC is used to maintain the receiving end voltage at a constant value For this purpose it uses a PI controller. The PI controller output is the X*c_order* of TCSC. A lookup table is used to convert X*c_order* to the corresponding firing angle.

Voltage Control by Using SSSC

In order to control the receiving voltage, the magnitude of the line current is multiplied by *Xs*.Where *Xs* is the output of the PI controller.

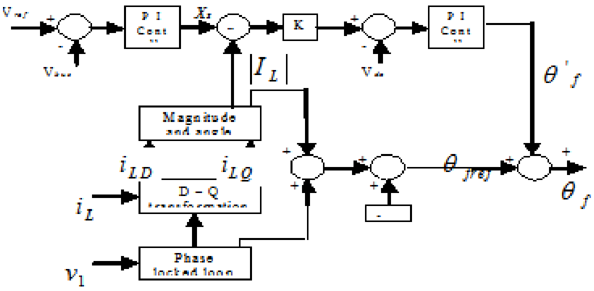

Figure 7: SSSC Voltage Controller

The PI controller input is difference between the reference voltage (13.8 kV) and the actual value measured at the receiving end (V*bus*). As the value of the receiving end voltage decreases, *Xs* increases and magnitude of the injected voltage increases. Fig 7 shows the block diagram of the controller.

SIMULATION STUDIES

In order to quantitatively investigate the performance of the control strategy, the system is subjected to a number of step changes in load and its response is plotted.

The load power (fixed + induction motor) is initially at 505 MW. The reference value of the TCSC is 13.8 kV (load bus voltage).

A disturbance of a step change in load of 50 MW was simulated through a change of induction motor input torque at 10th second. When the voltage comes below the set value the TCSC controller increases its reactance to maintain the voltage at the set value. It can be seen that when the induction motor load increases, the voltage reduces and the current through the capacitor increases and thereby the receiving end voltage. The above case was repeated with SSSC and performance. Fig 8 shows the terminal voltages and Fig 9 shows the voltage errors.

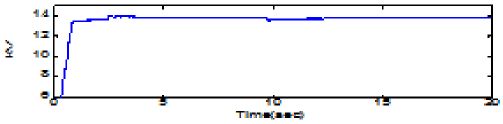

Figure 8(A): Terminal Voltage (TCSC)

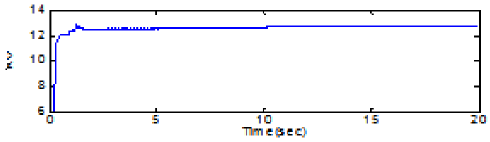

Figure 8(b) Terminal Voltage (SSS)

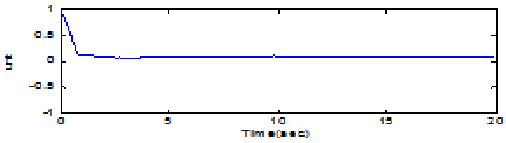

Figure 9(a): Voltage error (TCSC)

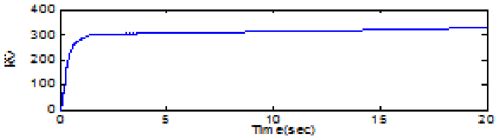

Figure 9(b): Voltage error (SSSC)

For the same load, the system is subjected to a 3 phase fault at the receiving end and the performance is analyzed. It can be observed that the fault level can be minimized by the use of TCSC, but the fault level is less compared to TCSC and performance is much faster in case of SSSC. Fig 12 shows the receiving end voltage of the system and Fig 13 and voltage error of the system.

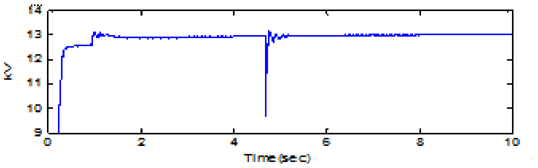

Figure 12(A): Receiving End Voltage (TCSC)

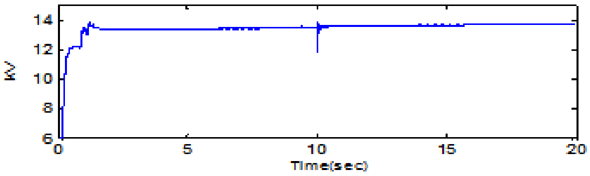

Figure 12(B): Receiving End Voltage (SSSC)

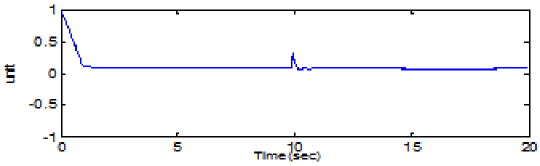

Figure 13(A): Voltage Error (TCSC)

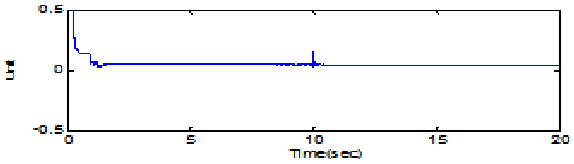

Figure 13(B): Voltage Error (SSSC)

Table 1 and table 2 shows the numerical values of Real Power and Voltages at various buses of the test system at 0.90 pf lag for different step changes of load for the case of TCSC and SSSC respectively.

Table 1(TCSC)

Real Power		Voltage		
Generator MW	Load MW	Receiving End	Sending End TCSC	Receiving End TCSC
100	97	15.01	532	516
200	196	14.40	522	508
300	290	13.8	506	498
400	376	13.22	500	493
548	532	12.55	475	469

Table 2 (SSSC)

Real Power		Voltage		
Generator MW	Load MW	Receiving End	Sending End SSSC	Receiving End SSSC
100	95	14.95	531	512
200	191	14.20	520	505
300	287	13.75	503	499
400	370	13.42	599	496
548	517	12.68	477	471

CONCLUSIONS

The main aim of this work is a comparative study of compensation for a long, bulk power carrying radial line supplying static as well as induction motor loads with TCSC and SSSC.

From the analysis, it is inferred that, by using TCSC or SSSC the power transfer capability can be substantially increased. Furthermore, it is established that TCSC/SSSC can be used to help in voltage regulation at the receiving end of the line. At high power factor and heavily loaded condition, TCSC/SSSC regulates the voltage with zero error over a rather small range of power. But if the power factor is lower, the range of power regulation is better. This is a desirable feature.

On comparison with TCSC, the presence of SSSC provides superior performance characteristic and application flexibility. It is observed form the results that, for an equal amount of change in dynamic load, the voltage injunction by SSSC is much faster and compensation is more accurate. Moreover, it shows that, damping of power oscillations is much better in SSSC compensated transmission line. But, considering the economical aspects, TCSC as a better choice for radial lines.

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