

The Impact of Line Resistance on the Performance of Controllable Series Compensator for Improving Voltage Stability

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ABSTRACT

In recent years controllable FACTS devices are increasingly integrated into the transmission system. FACTS devices that provide series control such as Controllable Series Compensator (CSC) has significant effect on the voltage stability of Electric Power system. In this work impact of line resistance on the performance of CSC in a single-load infinite-bus (SLIB) model is investigated. The proposed framework is applied to SLIB model and obtained results demonstrates that line resistance has considerable effect on voltage stability limits and performance of CSC.

Keywords

FACTS, CSC, Voltage stability limit, PV curves

1. INTRODUCTION

Power system voltage stability analysis has become very important for secure power system operation and satisfactory design as power industry's is undergoing revolutionary restructuring and a deregulation of electricity market [1, 2]. Renewable energy sources are increasingly integrated into distribution system to enhance security and stability. But presence on non-conventional resources has significant impact on line capacity of distribution network [3-5].

Flexible Alternating Current Transmission System (FACTS) devices are installed in power system network to improve the voltage stability as well as increase the power transfer [7]. It can be stated that the maximum power transmission over long lines is limited by the series reactive impedance of the line. [7] Series capacitive compensation results in reduced reactive line impedance and increased transmitted power. But with advent of FACTS technology, controllable series line compensation can be achieved power electronic devices for full utilization of transmission assets by altering the power flow in the lines.

FACTS devices can be classified by their response time and possibility to alter the circuit parameters like network admittance and voltage phasors. FACTS devices can also be classified on the basis of connection i.e. as parallel or series connection [7, 8]. Application of series controllable FACTS device CSC is discussed in this paper.

Series FACTS devices can increase the maximum power transfer capability of the line and can also damp out the oscillations. In this paper we see that the voltage stability of the system is improved by the application of CSC and also effect of line resistance is studied on the performance of CSC.

When the system is heavily loaded or the power transfer capability is reduced due to disturbances, in that case the lack of reactive power support makes the system voltage unstable which leads to voltage instability [11]. A system is said to be in voltage stable if at a given operating condition, for every bus in the system, the bus voltage magnitude enhances when supplied with additional reactive power. A system is voltage unstable if for at least one bus in the system, the bus voltage magnitude reduces as the reactive power injection at the same bus is reduced [11].

Voltage stability can be classified on the basis of extremity of the disturbance and also its duration. The application of the FACTS devices in transmission line plays very important role in the disturbances which occurs due to induction motors and HVDC converters [12]. Voltage stability analysis is done using continuation power flow (CPF) method is discussed in [13]. Voltage stability analysis can be done by using analytical and probabilistic methods [14]. Short term voltage instability phenomenon is discussed in paper [15], which shows that short term voltage instability occurs when the consumers have electrical motors and electronic controlled devices.

Authors in [16] studied the effect of a serial FACTS device on the voltage stability with the help of CPF. The understanding of the logical equations of FACTS devices (series) connected in single load infinite bus (SLIB) is discussed in [17]. Logical solutions to assess voltage of load bus connected in the SLIB model with an application of a CSC is discussed in [6]. All the aforementioned work neglected the effect of line resistance while analyzing voltage stability of system in presence of FACTS devices.

In this paper the line resistance has been considered for the analysis which results in reduction in the performance of CSC on the SLIB model. Mathematical model of SLIB is developed including CSC and line resistance and. Analytical equations are formulated to outline voltage instability. In order to analyze voltage stability upper and lower nose curves are plotted for different values of compensation parameter. Also the

comparison of the PV curves with and without resistance is presented for considered SLIB model.

This paper is organized as follows: Section II discusses Controllable Series Compensator and section III discusses mathematical modeling of CSC and Finally in section IV results are shown and discussed in detail.

2. CONTROLLABLE SERIES COMPENSATOR

A. Concept of controllable series compensator

The basic idea of series compensator is to decrease and increase the overall effective series transmission impedance from the sending end to receiving end depending upon the requirement.

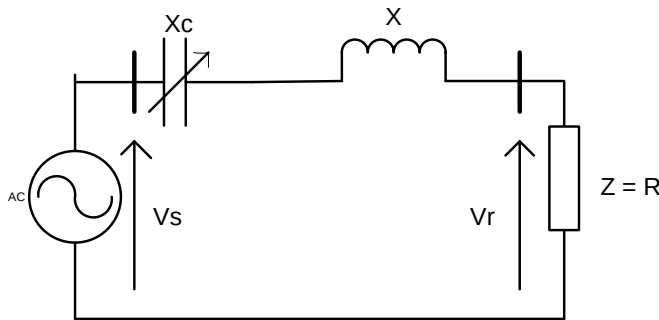


Fig - 1 Radial Transmission Line With Series Compensation

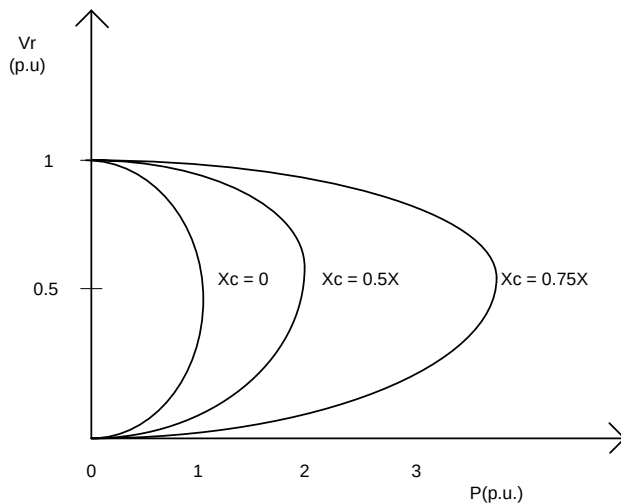


Fig - 2 Transmittable Power and Voltage Stability Limit of A Radial Transmission Line

Fig 1 shows a basic radial system with line reactance X , series compensating reactance X_c and load impedance Z [8]. The corresponding terminal voltage V_r versus power P plots, with unity power factor load at 0.50 and 75% series compensation are shown in Fig 2 [8]. The nose point at each plot given for a specific compensation level represents the corresponding voltage instability.

B. The SLIB model with the CSC

The application, connection and working principle of CSC is described in [9, 10]. The CSC works as a continuously controlled reactance X_c . The SLIB model with the CSC is presented in Fig 3, which is represented by the π model of the transmission line with the line parameters. After the addition of

CSC the two bus system becomes four bus system. The SLIB model with the CSC provides the simple approach for voltage stability assessment.

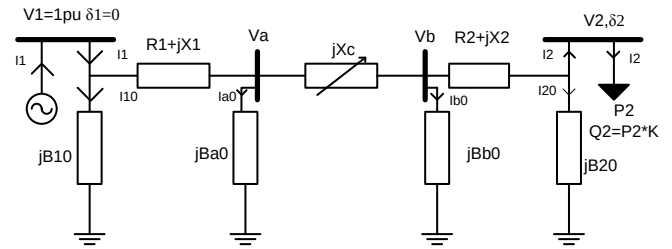


Fig - 3 The SLIB Model With The CSC

In large electric power system damping and load flow can be controlled by CSC.

C. Operating modes of CSC

1. **Capacitive mode:** In this mode the CSC delivers the reactive power to the system hence the voltage profile of the system can be improved. In that mode the values of the series reactance is negative i.e. $X_c < 0$
2. **Inductive mode:** In this mode the CSC absorbs the reactive power from the system hence the voltage profile of the system has been worsen. In that mode the values of the series reactance is positive i.e. $X_c > 0$

D. Approaches to Controllable Series Compensation

The series compensator can be used as a controlled voltage source which controls the current of the transmission line and is connected in series with the transmission line [8]. The series compensator can be used either as a variable reactive impedance or as a controlled voltage source in series with the transmission line. In case of series compensation the basic reference parameter is the line current. So the working of the series compensator is seen from the perspective of the line current. The series compensator can be approached in the following ways:

1. **Variable Impedance Type Series Compensators-** Variable impedance type series compensators make use of thyristor controlled capacitors or thyristor controlled reactors. GTO Thyristor-controlled series capacitor (GCSC), Thyristor-switched series capacitor (TSSC), Thyristor-controlled series capacitor (TCSC) falls under this category.
2. **Switching Converter Type Series Compensator -** Voltage source converter based series compensator which uses the converter based technology for series and shunt compensation [8]. A voltage-sourced converter with its internal control can be considered as a synchronous voltage source. It can produce sinusoidal voltage with controllable amplitude and phase angle, generate or absorb a reactive power. Static Synchronous Series Compensator (SSSC) is good example.

3. MATHEMATICAL MODELLING OF CSC

Voltage stability assessment is done using SLIB with CSC connected in series (Fig.3). The CSC is connected through the π model of the transmission line with the parameters $R_1, R_2, X_1, X_2, B_{10}$ and B_{20} .

The SLIB model shown in Fig.3 is suitable for voltage-instability studies because relation between load bus and its

voltage V_2 can be analyzed depending on the load flows and the characteristics of the loads, which can be voltage dependent or voltage independent. In order to understand, how the CSC affect the voltage V_2 , the CSC is placed at random distance from the slack bus, the parameters R_1 and R_2 , X_1 and X_2 , B_{10} and B_{20} as shown in Fig.3 have different values. Two bus SLIB model is converted to four bus model when series device connected between the buses A and B. On the buses A and B the suceptances B_{a0} and B_{b0} are connented as shown in figure for the model with the CSC.

The analytical equation for the voltage V_2 with the CSC (Fig.3) using the Kirchhoff current and voltage laws are formulated as follows:

$$I_1 = I_{10} + I_{A0} + I_{B0} + I_{20} + I_2 \quad (1)$$

$$V_2 = V_1 - (R_1 + jX_1)(I_{A0} + I_{B0} + I_{20} + I_2) - jX_{CSC}(I_{B0} + I_{20} + I_2) - (R_2 + jX_2)(I_{20} + I_2) \quad (2)$$

Currents expressions (1) and (2) can be expressed in terms of known variables P_2, Q_2, U_1 , with the parameters $R_1, R_2, X_1, X_2, B_{10}, B_{20}, B_{A0}$ and B_{B0} of the network and with the unknown variable-voltage V_1 [6]. After the introduction of the new denotations A_1, A_2, A_3 and A_4 [6] the voltage V_2 is written as:-

$$V_2^2(A_3 + jA_4 - 1) + V_2(V_1(\cos\delta_2 - j\sin\delta_2) + A_1 + jA_2) = 0 \quad (3)$$

Where A_1, A_2, A_3 and A_4 are given as follows:

$$A_1 = P_2(R_2(B_{B0}(X_1 + X_C) - 1) + B_{A0}(X_1 - B_{B0} \cdot X_1 \cdot X_C)) + R_1(B_{B0} \cdot X_2 - 1 + B_{A0}(X_2 + X_{CSC} - B_{B0} \cdot X_2 \cdot X_C)) + Q_2(B_{B0} \cdot (X_2 \cdot (X_1 + X_C) - R_1 \cdot R_2) - X_1 \cdot X_2 \cdot X_C + B_{A0}(R_1 \cdot R_2 \cdot (B_{B0} \cdot X_C - 1) + X_1(X_2 + X_C - B_{B0} \cdot X_2 \cdot X_C))) \quad (4)$$

$$A_2 = P_2 \cdot (B_{B0} \cdot X_2(X_1 + X_{CSC}) - R_1 \cdot R_2) - X_1 - X_2 - X_C + B_{A0} \cdot (R_2 R_1(B_{B0} \cdot X_C - 1) + X_1 \cdot (X_2 + X_C - B_{B0} \cdot X_2 \cdot X_C)) + Q_2(R_2(1 - B_{B0}(X_1 + X_C) + B_{A0} \cdot X_1 \cdot (B_{B0} \cdot X_C - 1)) + R_1(1 - B_{B0} \cdot X_2 + B_{A0} \cdot (X_2 \cdot (B_{B0} \cdot X_C - 1) - X_C))) \quad (5)$$

$$A_3 = B_{B0} \cdot (X_1 + X_C) + B_{A0} \cdot (X_1 B_{B0} \cdot X_1 \cdot X_C) + B_{20}(X_1 + X_2 + X_C + B_{B0}(R_1 \cdot R_2 \cdot X_2(X_1 + X_C) B_{A0} \cdot (R_1 \cdot R_2 \cdot (B_{B0} \cdot X_C - 1) + X_1 \cdot (X_2 + X_C - B_{B0} \cdot X_2 \cdot X_C)))) \quad (6)$$

$$A_4 = R_1(B_{A0} \cdot (B_{B0} \cdot X_C - 1) - B_{B0}) + B_{B0}(R_2 \cdot (B_{B0} \cdot (X_1 + X_C) - 1) + B_{A0}(X_1 - B_{B0} \cdot X_1 \cdot X_C)) + R_1(1 - B_{B0} \cdot X_2 + B_{A0} \cdot (X_2 \cdot (B_{B0} \cdot X_C - 1) - X_C)) \quad (7)$$

The analytical solution of (3) consists of four roots, of which those two with positive values of the voltage V_2 are interesting. These two solutions form the so-called upper and lower nose curve $V_2(P_2)$ for the SLIB model with a CSC [6].

4. SIMULATION RESULTS

Simulations for the proposed SLIB model are carried out on MATLAB to investigate the impact of CSC on the SLIB model. The impact of the operation of the CSC on the maximum power P_{2m} can be seen from the table 1. A negative value of the reactance X_C means that the CSC operates in the capacitive mode and a positive value of the X_C means that the CSC operates in the inductive mode. It can be seen that the voltage stability is improved when we operate the CSC in capacitive mode. The table shows the results when the line resistance is neglected.

Table 1 : Maximum Power for Different Values of The Parameter X_C for $R_1 = R_2 = 0$

S.NO	Series Compensation (X_C in pu)	Maximum Power (P_{2m} in pu)	Line Resistances (R_1 & R_2 in pu)
1.	0.16	1.133	0
2.	0.04	1.677	0
3.	0	2.002	0
4.	-0.04	2.489	0
5.	-0.08	3.299	0
6.	-0.12	4.908	0

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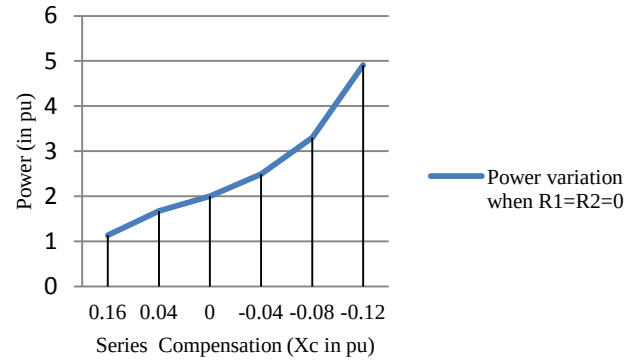


Fig – 4 Power Variation on The Different Values Of The Compensation Parameter X_C for $R_1 = R_2 = 0$

It can be observed from Fig.4 and Table 1 that when we apply the compensation in capacitive mode, the maximum power that can be transferred through the transmission line increases and when we apply the compensation in inductive mode, the maximum power that can be transferred through the transmission line reduces. As the line resistance is neglected so it can be concluded that the performance of the CSC is not affected by the resistance of the transmission line.

Simulation results for load voltage V_2 and P_2 in presence of CSC are shown in Fig 5 where each PV curve represents a specific value of the parameter X_C . The curves represent the voltage stability of the system and the point at which the voltage collapse occurs represent the point at which the maximum power is transferred.

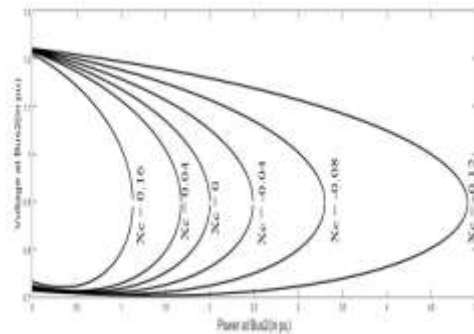


Fig – 5 PV curves for different values of the parameter X_C for SLIB with the CSC at $V_1 = 1$ pu

Effect of line resistance can be observed from Fig.6. It can be seen from the Fig 6 and Table 2 that the maximum power that can be transferred through line is reduced considerably. Also it can be seen that after adding the compensation, the maximum power that can be transferred through the transmission line is increased slightly. So the performance of CSC is inferior when line resistance of line is considered.

Table 2 : Maximum Power for Different Values of The Parameter X_c for $R_1=R_2=0.1\text{pu}$

S.NO	Series Compensation (X_c in pu)	Maximum Power (P_{2m} in pu)	Line Resistances (R_1 & R_2 in pu)
1.	0.16	0.589	0.1
2.	0.04	0.881	0.1
3.	0	0.943	0.1
4.	-0.04	1.009	0.1
5.	-0.08	1.077	0.1
6.	-0.12	1.141	0.1

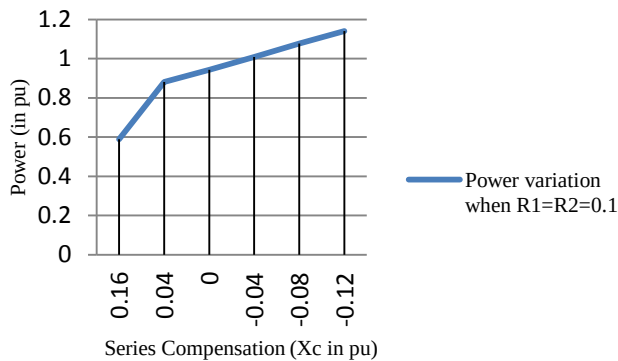


Fig – 6 Power Variation on The Different Values Of The Compensation Parameter X_c for $R_1 = R_2 = 0.1$.

The results of the simulation V_2 (P_2) in presence of CSC while the line resistance has taken into consideration is shown in fig 7.

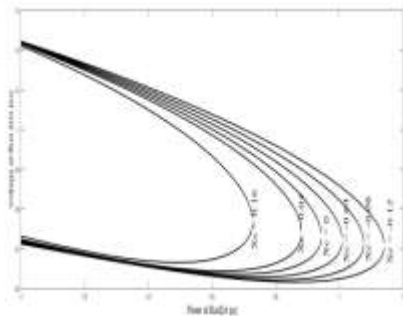


Fig-7 PV curves for different values of the parameter X_c for SLIB with the CSC at $V_1 = 1$ pu when $R_1=R_2=0.1$ pu

Fig 8 shows the comparison of power with the different values of resistances.

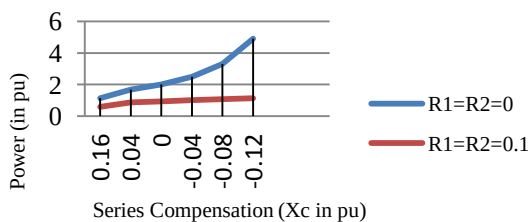


Fig – 8 Comparison of The Power Variation Curve for Different Values of The Resistances

5.CONCLUSION

Improvement of voltage stability is highly desirable for reliable electrical power system. FACTS is one of the best and promising solution available for reactive power compensation and improvement of voltage stability.

This paper investigates the performance of FACTS device CSC, when the resistance of the transmission line is taken into consideration. SLIB model is used for the analysis. The voltage stability and maximum power that can be transferred through the transmission line is calculated with and without considering the line resistances. It is found that when the line resistance is considered the voltage stability and maximum power transferred is reduced considerably. It can also be seen that performance of CSC is reduced. Hence it can be concluded that line resistance is the significant parameter for the analysis of voltage stability improvement through the FACTS devices.

6.References

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