Transient Response and Stability Analysis of Weak Power System Using Hybrid Compensator, STATCOM and SVC: A Comprehensive Comparison

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Abstract. Modern Power Systems are equipped with many distinct loads with huge transmission network. To ensure dynamic and transient generator and voltage stability in order to maintain the power system security is a major task of the power system Engineer. FACTS Controllers are most effective devices to ensure system security by enhancing the stability margins with reactive power support all over power system network. The major shunt compensation devices of FACTS are SVC and STATCOM, in this article the modelling of Hybrid compensator comprehended with SVC and GCSC as well and comparison among all of these devices have been made for weak power system.

This article dispenses the modelling and simulation of these shunts devices such as Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC) and Hybrid Compensator. The transfer function models of these devices have been derived from the first principles and obtained the transfer function models of weak power system. The dynamic response is obtained with the exact models of all these controllers for weak system, subsequently the root locus plots as well as bode plots have been obtained with MATLAB Programs and evaluated the performance of these devices and comparison is made. The Stability margins of the power system with all three devices have been obtained from the bode plots. The transient response of these devices have been assessed with time responses. The power system transient response as well as stability analysis using root locus and bode plots have been obtained and critically evaluated the merits and demerits of all these controllers. The power system performance has been improved with STATCOM as well as Hybrid Controllers.

Keywords: SVC · STATCOM · Hybrid compensator · GCSC and SVC · Stability margins · Modelling of SVG · Bode plots · Transient response of STATCOM · Comaritive analysis of FACTS devices

1 Introduction

Modern power systems are closely operating at its critical points due to exponenticial groth of power demand, due to this reason the power system performance playing a

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crucial role in power system security. The power system transient response as well as the stability and performance can be greatly effected by the use of FACTS devices viz. SVC, STATCOM and Hybrid Compensators. This article engrossed on the modelling and simulation ofthese devices, it's comprehensive coparitive analysis, focussing on it's transient response, root locus plots and bode plots for weak power system. The transfer function models have been derived for all these controlles along with it's time constants associated with all parts of the Compensators. These transfer function models have been used for the simulation studies, for the comparision of these three devices. The transient response is evaluated for weak system with three devices using transfer function models with the performance indices viz. peak overshoot and settling time. The subsequent part of the article deals with the root locus and bode plots and stability margins of these compensators for two kinds of systems. The gain and phase margins have been derived from the Matlab progrms and analysis of comparition have been made for all cases, [4–10].

2 STATCOM

The single line diagram of power system with STATCOM, generating station is feeding load through a transmission system with two buses, bus1 and bus2 at sending and receiving end respectively. The STATCOM schematic is connected to the receiving end bus as shown in Fig. 5, it may comprise of IGBT's and DC link capacitance, which is used to enhance the performance of the power system as illustrated in Fig. 1 below. The system should remain in synchronism even after being subjected to the disturbance, which involves output power oscillates reflected in rotor oscillations [3–11].

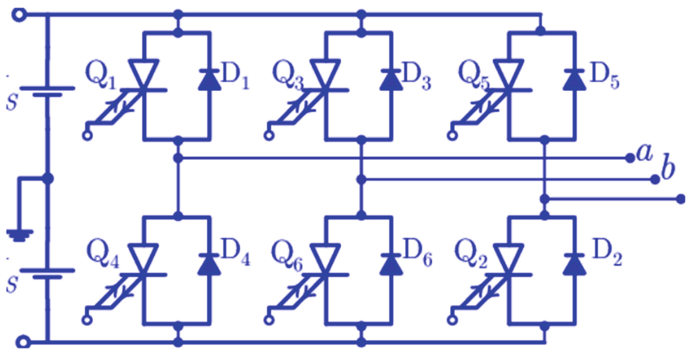

Fig. 1. Schematic diagram of STATCOM

2.1 Mathematical Modelling of DSTATCOM

The equations for active power, reactive power of STATCOM are as follows;

Consider V_t = system terminal voltage
V_{st} = STATCOM output voltage
X_L = Inductive reactance
V_C = DC capacitor voltage

$$P = \frac{V_t V_C}{X_L} \sin\alpha \tag{1}$$

$$Q = \frac{V_t V_t}{X_L} - \frac{V_t V_C}{X_L} \cos\alpha \tag{2}$$

The equation of DSTATCOM on DC side can be given as;
The mathematical equations of DSTATCOM can be expressed as;

L = series inductance
R = series resistance
i_{ac}, i_{bc}, i_{cc} are output currents of DSTATCOM
V_{ac}, V_{bc}, V_{cc} are output voltages of DSTATCOM
V_{ta}, V_{tb}, V_{tc} are terminal voltages

$$L\frac{di_{ac}}{dt} = Ri_{ac} + V_{ac} - V_{at} \tag{3}$$

$$L\frac{di_{bc}}{dt} = Ri_{bc} + V_{bc} - V_{bt} \tag{4}$$

$$L\frac{di_{cc}}{dt} = Ri_{cc} + V_{cc} - V_{ct} \tag{5}$$

3 Static Var Compensator (SVC)

3.1 Description of Working and Power Circuit of SVC

The single line diagram of power system with SVC, generating station is feeding load through a transmission system with two buses, bus1 and bus2 at sending and receiving end respectively. The SVC schematic is connected to the reciving end bus, it may comprise of SCR's, which is used to enhance the performance of the power system as depected in Fig. 3 below [11] and [12].

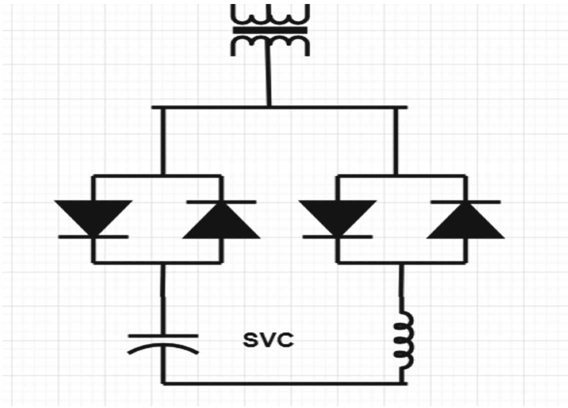

Fig. 2. Schematic diagram of SVC

3.2 Mathematical Modelling of SVC

The susceptance of the device can be controlled with the control of the firing angle of the TCR and Fig. 2. Shows the Variable susceptance of SVC [21–28].

$$B_{SVC} = B_{TSC} - B_{TCR} \tag{6}$$

$$B_{TCR} = B_L((\pi - 2\alpha - \sin\alpha)/\pi) + B_C \tag{7}$$

$$Q_{SVC} = ((X_C[2\pi - \alpha + \sin 2\alpha] - \pi X_L))/((\pi\ X_C X_L)) \tag{8}$$

In steady state an SVC can be treated as a reactive power injection source, which can be presented as the following mathematical expression:

$$Q_{SVC} = V_T(V_T - V_{ref})X_{SL} \tag{9}$$

where X_{SL} is the slope of voltage control characteristic, Vt is the terminal voltage of SVC and Vref is the reference voltage, the above Equation can be rewritten as:

$$Q_{SVC} = B_{SVC} \times V_{ref2} \tag{10}$$

The value of B_{SVC} can be varied between minimum and maximum susceptance and the reactive power generated by SVC is given by

$$Q_{SVCmin} \leq Q_{SVC} \leq Q_{SVCmax} \tag{11}$$

4 Hybrid Compensator

4.1 GTO Controlled Series Capacitor (GCSC)

The GCSC schematic is described with the antiparallel combination of GTO Thyristors used to control the series injected voltage with the feeder as depicted in the below figure.

The reactance and voltage variation of GCSC with the variation of the conduction angle as depicted by the following Eqs. (1) and (2) respectively. The harmonics injected by the device is illustrated in the Eq. (3) and the voltage wave form of complete control of the device is illustrated in Fig. 4 comprising of parts a, b and c as (a) GCSC Schematic circuit, (b) One complete cycle, (c) total current of GCSC. The total current shown in the waveform comprises of harmonics since the conduction angle is rapidly adjusted for controlling series voltage of the system [1–3].

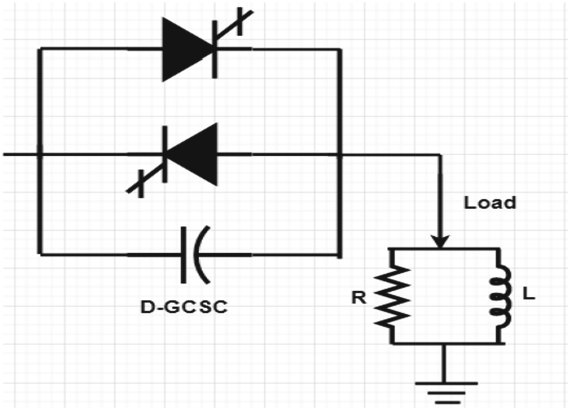

Fig. 3. Schematic diagram of GCSC

$$\mathrm{Xc}(\gamma) = \frac{1}{wC}\left(1 - \frac{2\gamma}{\pi} - \frac{\sin(2\gamma)}{\pi}\right) \tag{12}$$

$$V_{CF}(\gamma) = \frac{I}{wC}\left(1 - \frac{2\gamma}{\pi} - \frac{\sin(2\gamma)}{\pi}\right) \tag{13}$$

$$V_{Cn}(\gamma) = \frac{I}{wC}\frac{4}{\pi}\left(\left(\frac{\sin(\gamma)\cos(n\gamma) - \mathrm{nsin}(n\gamma)\cos(\gamma)}{n(n^2 - 1)}\right) - \frac{\sin(2\gamma)}{\pi}\right) \tag{14}$$

4.2 Hybrid Compensator

Hybrid Compensator is consists of one variable impedance series compensator i.e. GTO Controlled Series Capacitor (GCSC) and Static Var Compensator (SVC) as illustrated in Fig. 5. His hybrid compensator is used in the weak power system to improve its transient response and system stability which is compatible to that of the SATCOM [1–3].

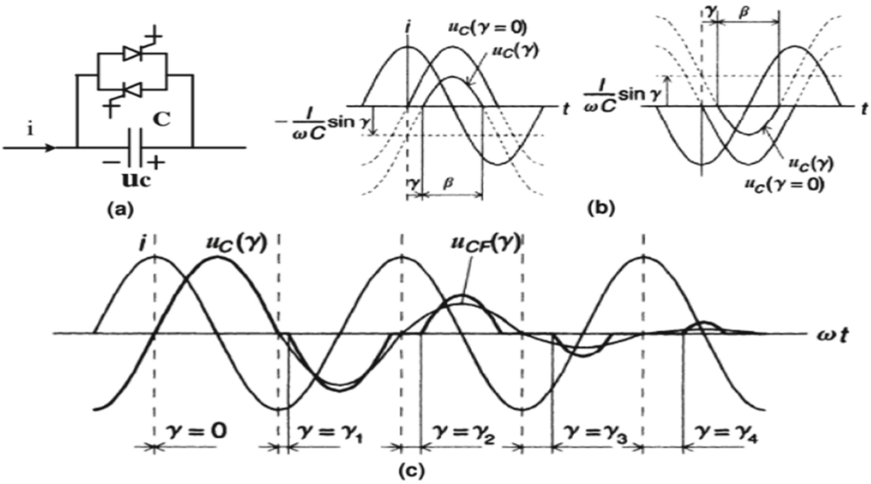

Fig. 4. (a) GCSC Schematic circuit, (b) One complete cycle, (c) total current of GCSC

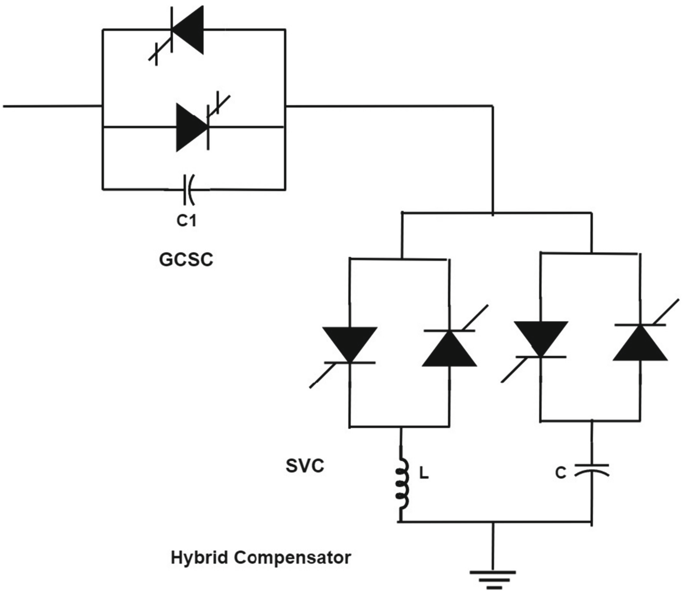

Fig. 5. Schematic diagram of Hybrid Compensator

5 Transfer Function Model of Static VAR Generator (SVC/STATCOM)

The transfer function model of Static Var Generator for both SVC and STATCOM have been shown in Fig. 3. It comprising of the regulator transfer function G1 with PI controller time constant T1, droop k value in typical range of 1 to 5%, Controller transfer function with transport dealy Td, which is different for both the controllers and feed back transfer function of measuring circuit with time constant of T2 respectively as depicted in Fig. 3. The transport delay is very low for the STATCOM and it very significant in infunecing the power system performance.

5.1 Transfer Function Model of Voltage Regulator

The transfer function model of the Voltage regulator is obtained with slope of the VI Characteristics of the STATCOM and SVC, which is in the range of 1 to 5% as illustrated below in the equation, where the T1 is the time constant of the PI Controller, typically it is in range of 10 to 50 ms as depicted in Fig. 6 below.

$$G_1 = \frac{1/k}{1 + sT_1}$$

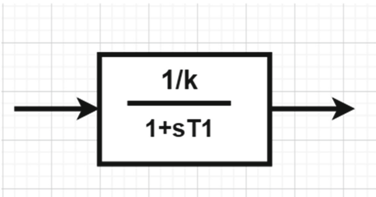

Fig. 6. Voltage regulator model

5.2 Transfer Function Model of Static Var Generator

The transfer function model of the Static Var Generator viz. STATCOM and SVC is obtained with the transport delay time Td of the STATCOM and SVC as illustrated below in the equation, where the Td is transport delay of the STATCOM and SVC Controller, typically it is in range of 0.5 ms for STATCOM and 5.55 ms for the SVC. This transport delay makes the distinction between both of the controllers as illustrated in the following equation and block diagram as shown in Fig. 7 below.

$$G_2 = \frac{1}{1 + sT_d} \tag{15}$$

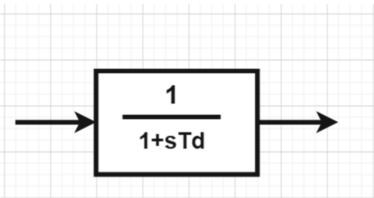

Fig. 7. SVG model

5.3 Transfer Function Model of Feedback Circuit

The transfer function model of the feedback measurement circuit is obtained with the delay time in the measurement as T2 as illustrated below in the equation, where the T2 is the delay in the measuring circuit, typically it is in range of 8 to 16ms as illustrated in the following equation and block diagram as depicted in Fig. 8 below.

$$H = \frac{1}{1 + sT_2} \tag{16}$$

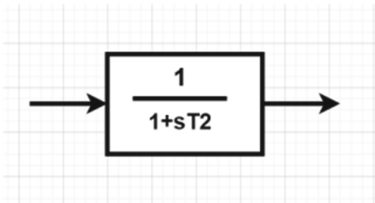

Fig. 8. Measuring feedback model

5.4 Complete Transfer Function Model of STATCOM and SVC

The complete transfer function model of an Static Var Generator either STATCOM or SVC, since same model is equally valid for both the controllers with different transport delay time is depicted in the following Fig. 8. This transfer function model is comprising of two input signals, one is the reference voltage i.e. Vref and the second one is SVG output voltage as disignated Vo and one output as terminal voltage of the power system. The slope of the VI charectoristics of SVG is represented as k and is explained in the previous part of the article, furter the power system reactance, these two parameters will discriminate between weak and strong power systems. The typical values of reactance for strong system is about 4 to 5, and weak system in per unit values and for weak system it is about 9 to 10 p.u as taken in simulation study [5–10] (Fig. 9).

$$\mathrm{P} = \frac{\mathrm{V}_1 V_2}{\mathrm{X_T}} \sin \delta \tag{17}$$

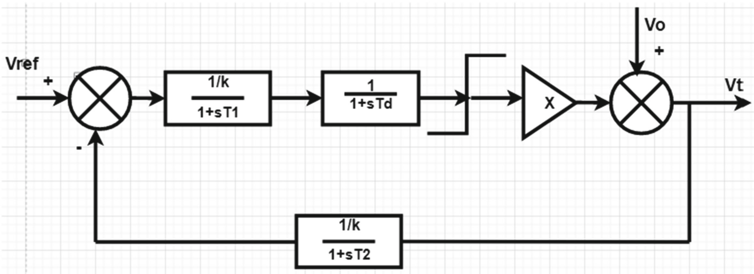

Fig. 9. Transfer Function model of SVG (SVC and STATCOM)

6 Case Study and Results

The Simulink models have been designed and developed for weak power systems along with the SVC, STATCOM and Hybrid Compensators as illustrated in Fig. 10 below, to get the comarion of both Transient responces on same graph, a mux with three inputs, one is from STATCOM, the second is from SVC and the third is from Hybrid Compensator are connected to one scope, in which the comparitive plot is achieved.

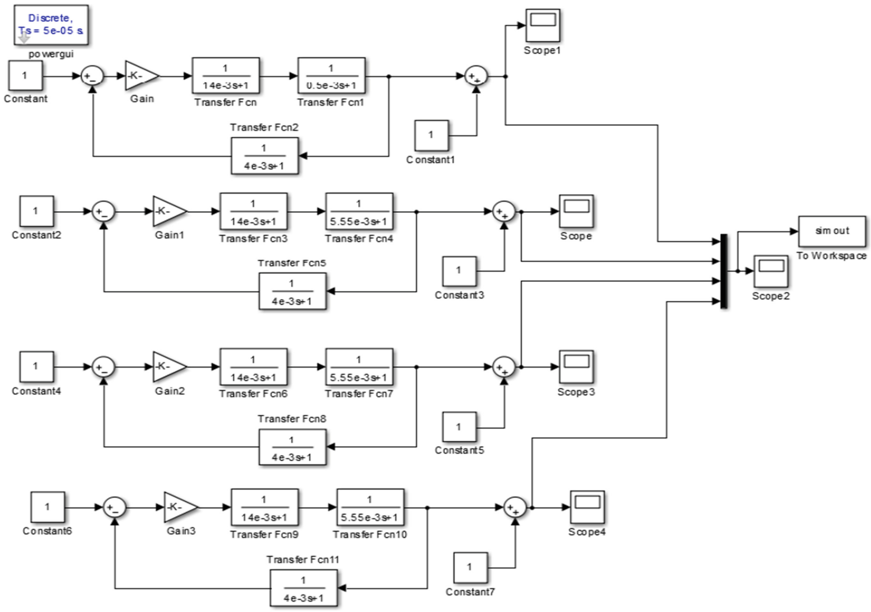

Fig. 10. Simulink Model weak system with SVC, STATCOM and Hybrid device with two distinct firings of GCSC and SVC

6.1 Comparative Analysis of SVC, STATCOM and Hybrid Compensator Transient Responces for Weak Power System

The Transient responses of the SVC, STATCOM and Hybrid Compensator for the weak power sytem with two simultanious inputs of reference voltage and output voltage of the Compensators as depicted in following Fig. 11. The weak power system with SVC is completely unstable, The peak overshoot of STATCOM is 94.56% is more when compared to the Hybrid Compensator, which is 70.4%. The settling time is concerned, there is no settling time for SVC hence the system is unstable. The STATCOM settling time is 0.06S and is very low comared to Hybrid Compensators settling time 0.107S and both systems are stable as depicted in the Fig. 10 below and the steady state error is more for Hybrid Compensator. The steady state error of Hybrid Compensator is decreased with different set of conduction, firing angles of GCSC and SVC respectively and the settling time is increased to a higher value for it as illustrated in the Fig. 12 below.

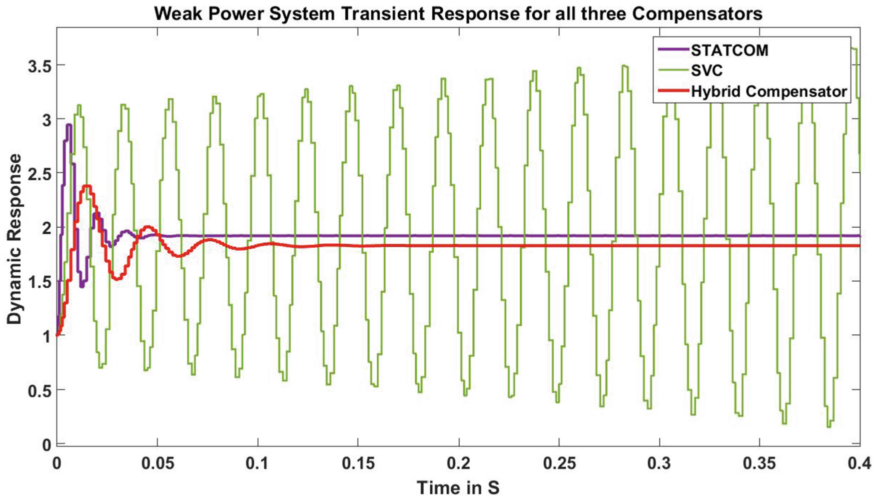

Fig. 11. Dynamic Responses of STATCOM and SVC for strong system

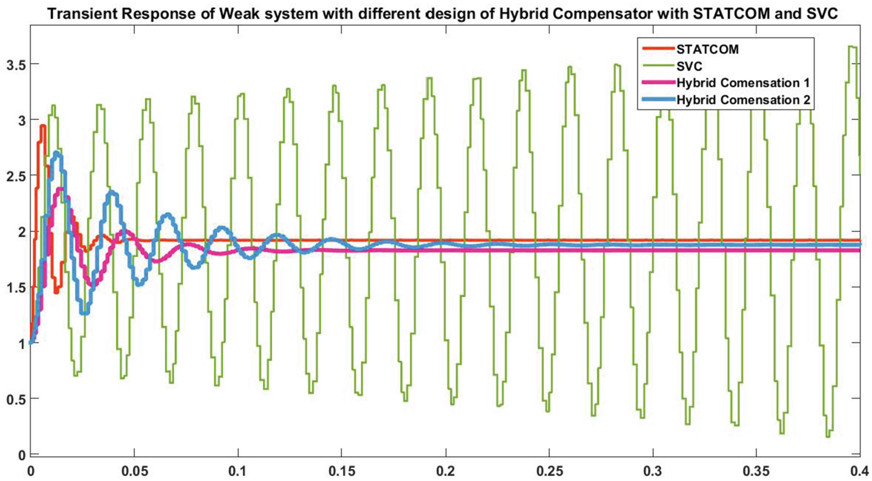

Fig. 12. Transient Response for two different firing angles of Hybrid Compensator

6.2 Comparative Analysis of SVC, STATCOM and Hybrid Compensator Root Locus Plots for Weak Power Systems

The root locus plots of all three compensators for the weak power sytem with reference voltage as depicted in following Fig. 13. The root locus plots of SVC indicates that for weak system and it indicating small relative stability margins. Figure 14 below, which indicates that that the system is stable with STATCOM and relative margin of stability is high. Figure 15 shows the Root locus plot of Hybrid Compensator with conduction angle 1 for weak power system and Fig. 16. depicts the Root locus plot of Hybrid Compensator with conduction angle 2 for weak power system but for both relative stability margin is higher than SVC and lower than STATCOM.

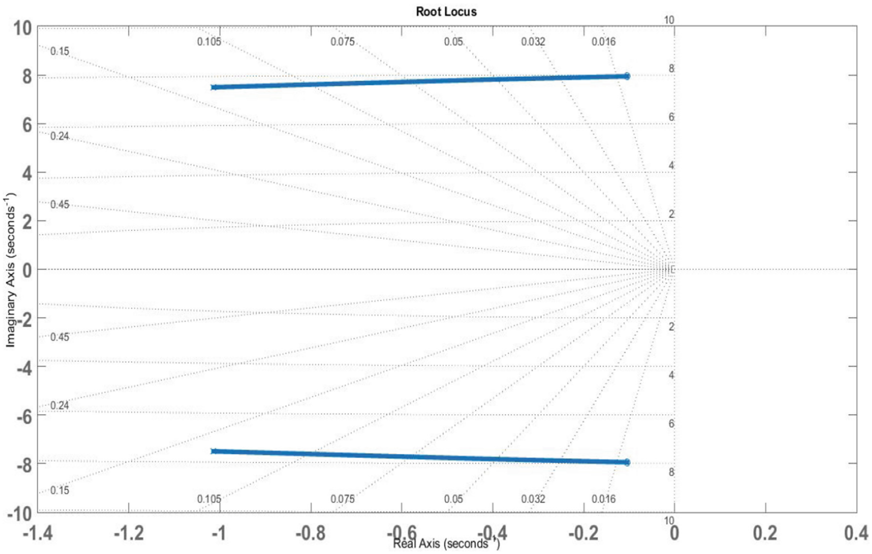

Fig. 13. Root locus plot of SVC for weak power system

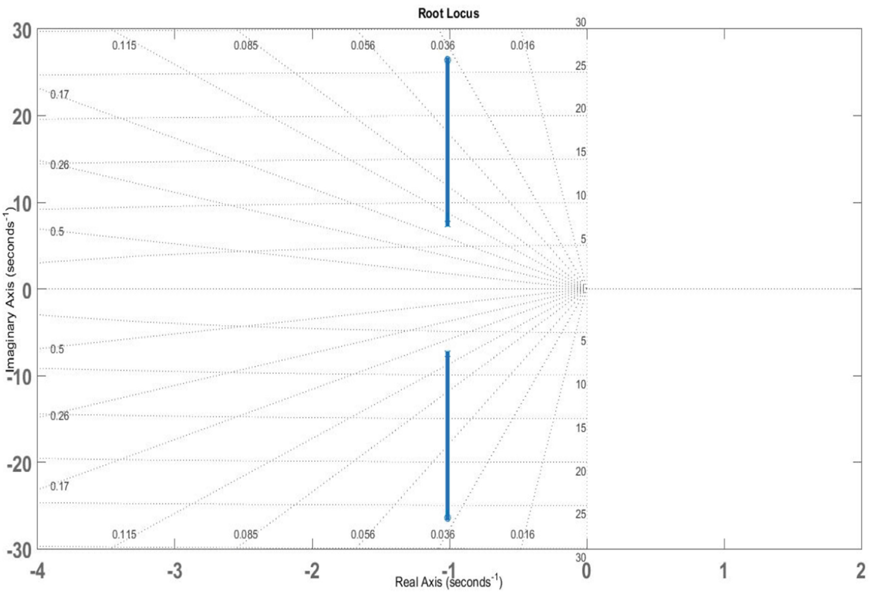

Fig. 14. Root locus plot of STATCOM for weak power system

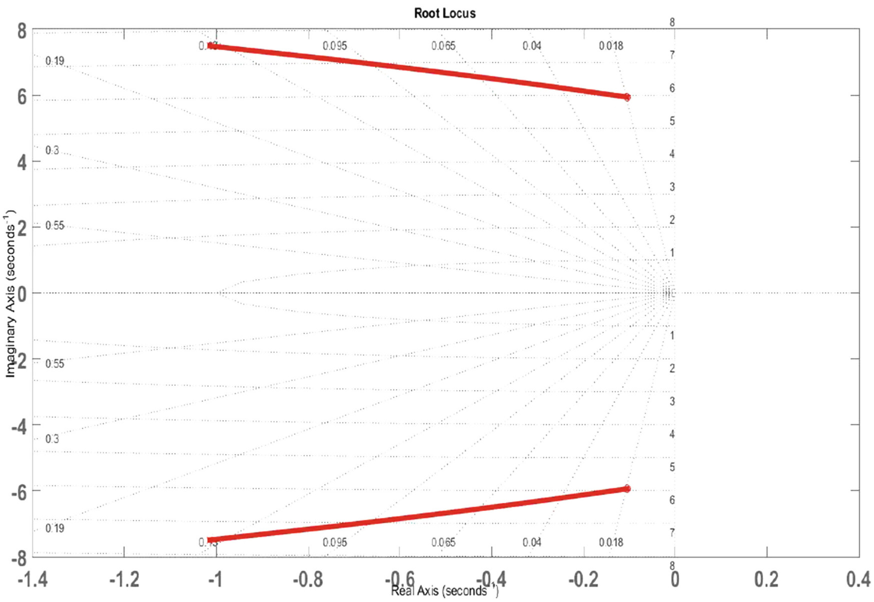

Fig. 15. Root locus plot of Hybrid Compensator with conduction angle 1 for weak power system

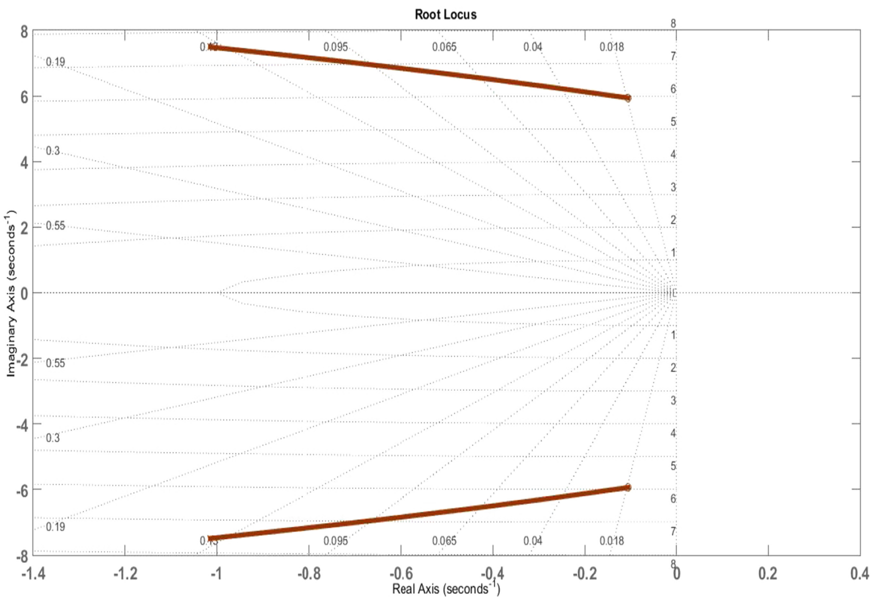

Fig. 16. Root locus plot of Hybrid Compensator with conduction angle 2 for weak power system

6.3 Comparative Analysis of SVC, STATCOM and Hybrid Compensator Using Bode Plots for Weak Power Systems

The bode plots of all three compensators for the weak power sytem with reference voltage as depicted in following Fig. 17. The bode plots of SVC shows that the system is unstable with negative phase margin. The STATCOM response shows that the system is completely stable with phase margin of 13.9976° and with infinity gain margin. The bode plots of the Hybrid Compensator also showing negative margins and hence among all compensators SATATCOM performance is better, whereas the system can be made stable with Hybrid Compensator and the system is completely unstable with SVC alone (Figs. 18, 19 and 20).

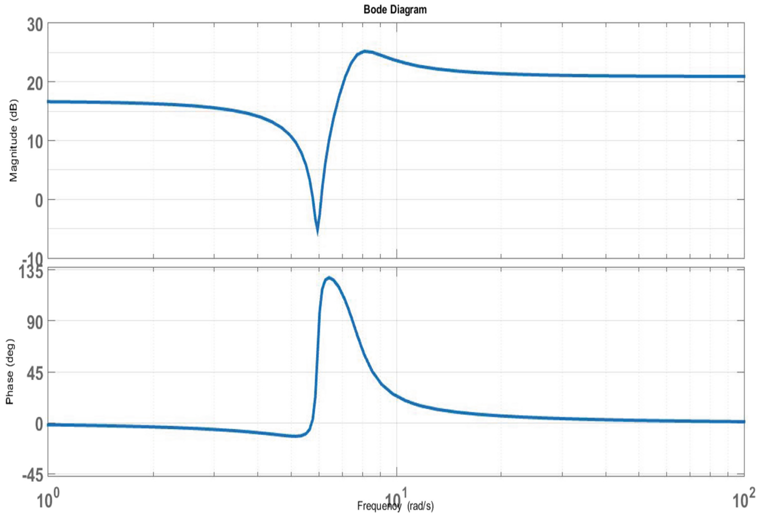

Fig. 17. Bode plot result of SVC for Strong system

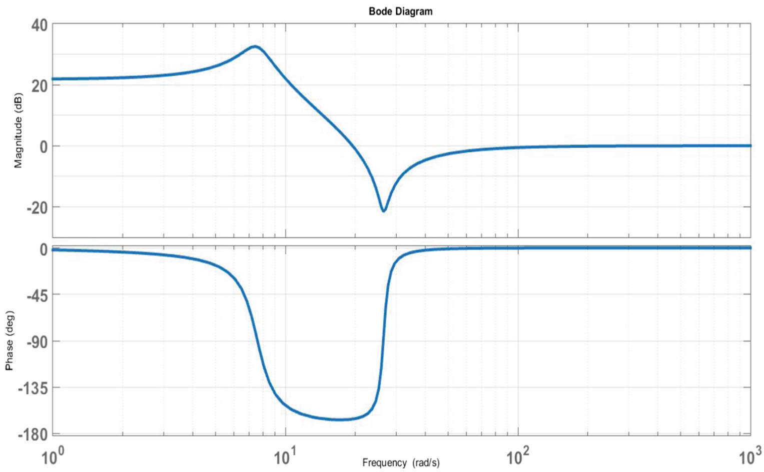

Fig. 18. Bode plot result of STATCOM for weak system

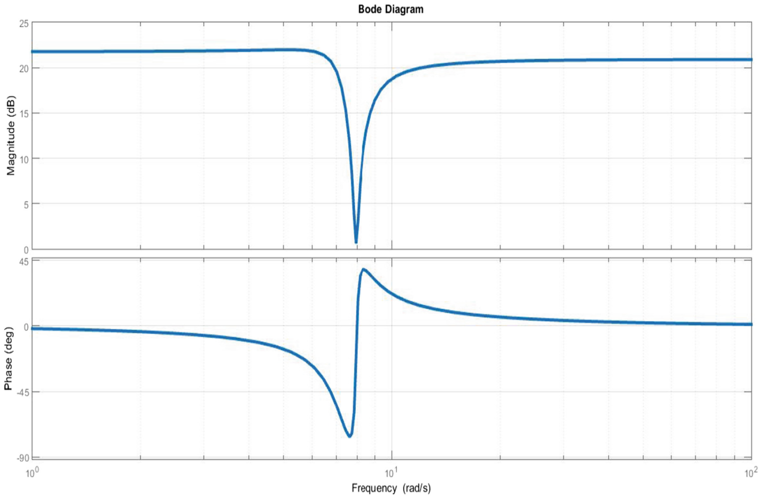

Fig. 19. Bode plot result of Hybrid device with conduction angle 2 for weak system

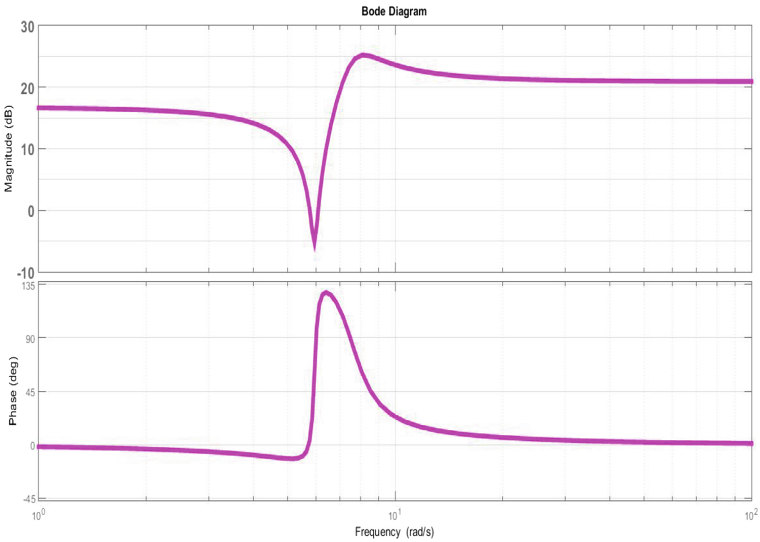

Fig. 20. Bode plot result of Hybrid device with conduction angle 1 for weak system

7 Conclusions

This article dispense the modelling and simulation of three devices viz. one is Static Synchronous Compensator (STATCOM) and the second is Static Var Compensator (SVC) and the last is Hybrid Compensator comprised of GCSC and SVC. The transfer function models of these devices have been derived from the first principles. The transient response is obtained with the exat model weak system. The transient performance of all devices have been simulated and results have proven that the STATCOM is relatively more stable compared to other two devices. The system is completely unstable with SVC and it can be made stable with hybrid compensator comprising of GCSC and SVC, which proved by simulation resopnces. Subsequently the root locus plots as well as bode plots have been obtained with MATLAB Programs and evaluated the performance of these devices and comparision is made.

The root locus plots of all three compensators for the weak power sytem with reference voltage have been presented and proves that the STATCOM is stronger device compared to other two and Hybride compensator has the better margin compared to SVC. The bode plots of all three compensators for the weak power sytem with reference voltage have been presented and proves that the system is Stable only for STATCOM and is unstable for other two devices. The Hybrid device transient response as well as root locus plots shows that the system is stable and can be accepted, where as only root locus plots of SVC are accepted and other two plots of SVC are not accepted.

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