Modelling and Design of Static Compensator and UPFC Based FACTS Devices for Power System Oscillations Damping and Voltage Compensation

D. V. N. Ananth, L. V. Sureshkumar, and Manmadhakumar Boddepalli

Abstract In this paper, four synchronous generators in a bi-area system generally known as Kundur system is considered for analysis of power oscillations and voltage dips. There are two parallel lines available for this network. Here, STATic COMpensator (STATCOM) which is a shunt device and Unified Power Flow Controller (UPFC) a hybrid shunt and series combination FACTS device is compared to identify better power oscillation damping and voltage compensating device when a grid disturbance is occurred. A very low impedance symmetrical fault occurs at the middle of the transmission network and these FACTS devices are kept near the fault but towards the second area. This fault creates surge currents that will flow in all lines, creating voltage dip across the lines, real and reactive power oscillations in the synchronous generators and quickly stability of the total system is influenced. These STATCOM and UPFC controller will act like low impedance path for the fault current and will divert the fault current which will in return stored in the converter capacitor is injected in the form of current by shunt device and voltage injection by the series device. Hence overall system profile and stability is improved. Results prove that the compensation in area-2 is better. These FACTS devices are kept after the fault and among these two devices, UPFC found better with effective compensation. The study is observed in two cases with first using a STATCOM, and second case with UPFC.

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1 Introduction

The main role of the transmission network is to have better reliability with lesser losses and higher stability margin. For attaining desired stability margin, the system must operate with reserve margin to overcome overloading or over current during load and fault transients [1]. But, this factor is not recommended for economical reason hence the transmission lines and generators will operate near its nominal rating. To ensure nominal power flow and also to attain high stability margin, FACTS technology is promising [2]. These FACTS devices capital cost is high but having very lesser running cost. Among these FACTS family Static Var Compensator, STATCOM and UPFC are better choice for voltage compensation, stability improvement and power flow improvement [3]. Static compensator (STATCOM) is a shunt device capable of voltage and reactive power regulation, and effective in power oscillation damping for a synchronous generator system under any transient conditions like switching and faults [4–6]. The series FACTS devices like Static Synchronous Series Compensator (SSSC) is a voltage injecting device and can be placed anywhere in the transmission network has advantages than STATCOM in terms of voltage compensation, stability improvement, power oscillations damping (POD) and operate at lower rating [7].

For high power electric generation, steam or hydro turbines are coupled to salient pole or cylindrical rotor synchronous generators. These FACTS devices must be losses-free, quicker in response, must not create new disturbance or aid to disturbance already in the system, but must compensate voltage and improve its profile [8–10]. In this paper, four synchronous generators in a bi- area system generally known as Kundur system is considered [11, 12]. The comparison of SVC and STATCTCOM in small signal stability for single machine infinite bus system (SMIB) using Eigen value and bifurcation methods and their effectiveness is studied in [13]. Nonlinear design of PSS and STATCOM using cuckoo search algorithm [14] and few authors observed POD is effective when advanced robust controllers like H-infinity ($H\infty$) controllers, fuzzy controllers, neural networks, meta-heuristic multi-objective controllers will be very helpful [15–19]. Among FACTS family STATCOM plays a major role in damping power system oscillations [17, 18]. These controllers will be faster, accurate and lesser parameter dependant and act according to the system and its fault behavior.

2 Configuration of the System

The equivalent Kundur power system test single line diagram is shown in Fig. 1. This system consists of four generators of equal rating. The impedances $Z1$ to $Z3$
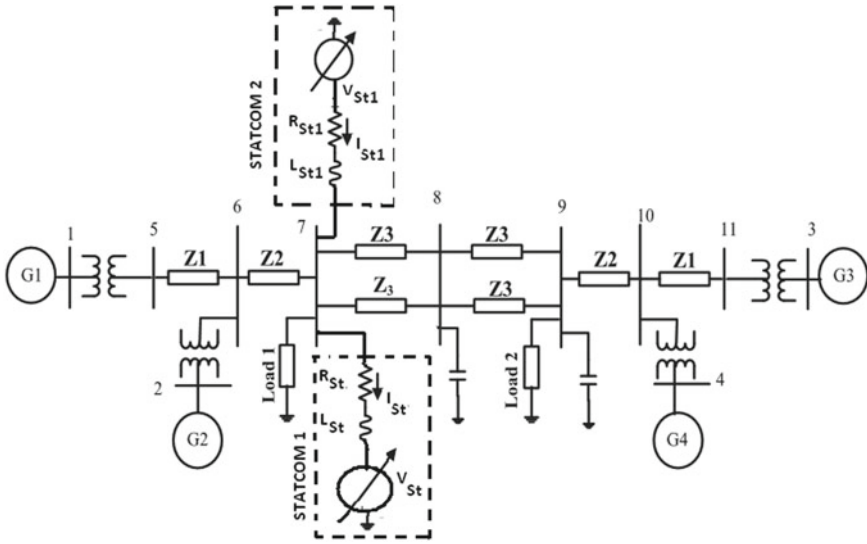
Fig. 1 Kundur four generators two area 11 bus system with STATCOM

represent transmission line passive components. The generator, line, transformer and load parameters are taken from [11].

2.1 Synchronous Generator Block Diagram

The synchronous block diagram is shown in Fig. 2. The system consists of governor, voltage controller and system stabilizer. The difference between desired and actual
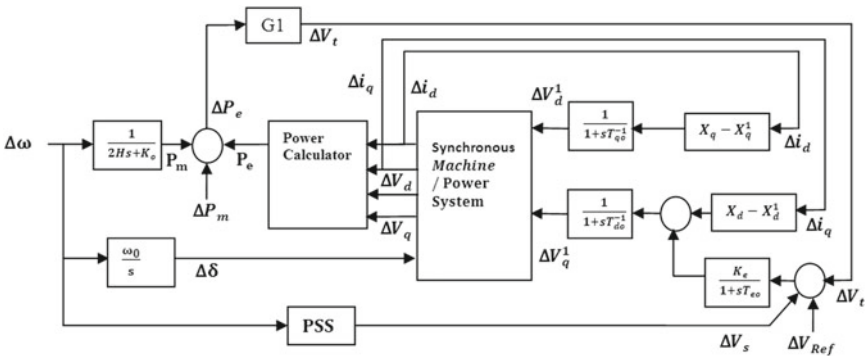

Fig. 2 The free body diagram of the synchronous generator with PSS and AVR
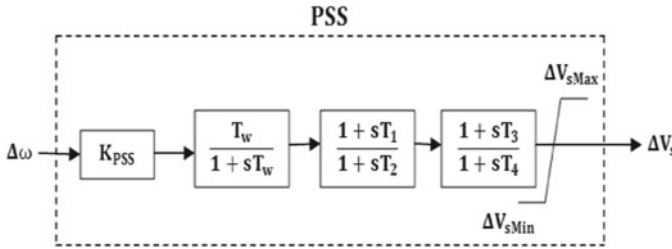
Fig. 3 The speed regulator based 5th order PSS representation

speed is said to be speed error, it is controlled by speed governor. Based on the difference in the speed ($\Delta\omega$), mechanical output (P_m) varies. From two space analysis, output power can be derived.

2.2 Power System Stabilizer (PSS)

The block diagram representation of 5th order PSS lead-lag compensator is shown in Fig. 3. If a disturbance occur to power system, if the system regains its pre-disturbance state is defined as stable. During or after disturbance, oscillations in generator parameters take place and if these oscillations are damped quickly then system comes to steady state operation. For oscillations damping PSS with lead-lag compensator type is used. K_{pss} is PSS gain constant; T_w is washout time constant, its value is about 30 s [15]. Lower than this value oscillations persist. For compensating excitation control system and also to maintain local phase lag, lead time constants are to be tuned and to improve stability lag time constants are used. For active power oscillations damping, the relationship with mechanical power flow change can be represented as in Eq. (1) as

$$\frac{2HS_B}{\omega_0}\frac{d\omega_s}{dt} = P_{turbine} - P_{ref} - K(\omega_1 - \omega_0) \tag{1}$$

Equation (1) is common representation of the synchronous generator under equilibrium with $\frac{d\omega_1}{dt}$ is zero when $P_{ref} = P_{turbine}$ and $\omega_s = \omega_1 = \omega_o$, where ω_1 is angular frequency of transmission lines in area-1 measured using phase locked loop (PLL).

2.3 Statcom

The static compensator is abbreviated as STATCOM which is a shunt connected voltage source converter (VSC) for a transmission line system connected where voltage and power flow profile improvement is necessary. The STATCOM is effective

than SVC in terms of compensation, stability improvement and can quickly control reactive power is damp power oscillations characteristics. The PSS and exciter control system are used to damp generator as well as inter-area oscillations to a maximum level and to enhance transient stability of complete power system.

2.4   UPFC-Unified Power Flow Controller

Among all FACTS devices, UPFC is said to be more versatile and robust [20]. It is due to the fact that it contains both series and shunt devices, disadvantages of any series or shunt can be compensated by the combination of the two. The advantages of UPFC are instantaneous control and can be designed with chatter-free characteristics, finite convergence time, smooth and faster control, effective to external disturbances.

3   Analytical Analysis of the System with STATCOM

The Dynamic equations of the power system with all parameters are taken from Fig. 4 and from [11]. The sub-script 's', 'st' and 'r' represents supply, STATCOM and receiving terminals. The voltage and current are represented with V and I and passive components like resistance, inductance and capacitance with R, L and C. STATCOM is having variable voltage, hence represented as shown in figure with variable mark Let δ_i is load angle and angular frequency of generator and STATCOM is represented as ω_i and ω_t at terminal "t" [11].

Fig. 4 Single line diagram of two area transmission and receiving system with a STATCOM at the midpoint
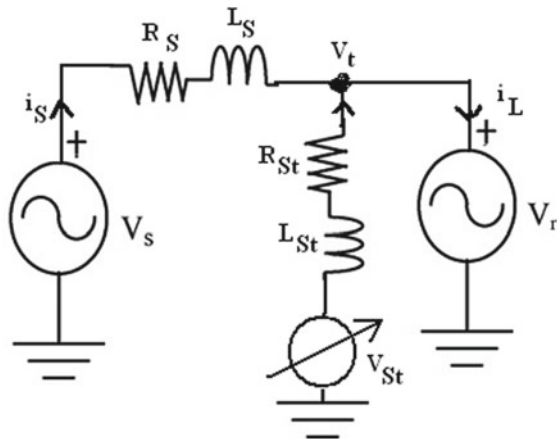
3.1 Generator Modelling

The dynamic equations of the alternator will be helpful in understanding the behavior under steady-state and transient conditions and also help in identifying and control the parameter dependency variables. The load angle in terms of angular speed change is shown in Eq. (2).

$$\frac{d\delta_i}{dt} = \omega_i - \omega_t \tag{2}$$

Similarly, the ith generator angular speed and its voltages are shown from Eqs. (3) to (8).

$$\frac{d\omega_i}{dt} = \frac{\omega_s}{2H_i}\left[T_{mi} - E_{qi}^1 I_{qi} - (X_{di}^1 - X_{qi}^1)I_{di}I_{qi} - E_{di}^1 I_{di} - D_i(\omega_i - \omega_b)\right] \tag{3}$$

$$\frac{dE_{qi}}{dt} = \frac{1}{T_{doi}^1}\left[E_{fdi} - E_{qi}^1 - (X_{di} - X_{di}^1)I_{di}\right] \tag{4}$$

$$\frac{dE_{di}}{dt} = \frac{1}{T_{qoi}^1}\left[-E_{di} + (X_{qi} - X_{qi}^1)I_{qi}\right] \tag{5}$$

$$\frac{dE_{fdi}}{dt} = \frac{1}{T_{Ei}}\left[-(S_{Ei}(E_{fdi} + K_{Ei})E_{fdi} + V_{Ri}\right] \tag{6}$$

$$\frac{dR_{fi}}{dt} = \frac{1}{T_{Fi}}\left[\frac{K_{Fi}}{T_{Fi}}E_{fdi} - R_{fi}\right] \tag{7}$$

$$\frac{dV_{Ri}}{dt} = \frac{1}{T_{Ai}}\left[-V_{Ri} + K_{Ai}R_{fi} - \frac{K_{Fi}K_A}{T_{Fi}}E_{fdi} + K_{Ai}(V_{refi} - V_i)\right] \tag{8}$$

Under equilibrium state, the voltage of direct and quadrature is represented as in Eqs. (9) and (10) as

$$E_{di}' - V_i\text{Sin}(\delta_i - \theta_i) - R_{si}I_{di} + X_{qi}'I_{di} = 0 \tag{9}$$

$$E_{qi}' - V_i\text{Cos}(\delta_i - \theta_i) - R_{si}I_{qi} + X_{di}'I_{qi} = 0 \tag{10}$$

Equations (9) and (10) are satisfactory under steady-state conditions, but in the transient state, they are not equal to zero.

3.2 Dynamic Modelling of STATCOM as Current Injecting Device

The STATCOM which is a shunt device will inject current at the point of coupling and is represented using Eqs. (11) and (12) as

$$\frac{\mathrm{d}I_{std}}{\mathrm{d}t} = \frac{-\omega_s R_{st}}{X_{st}} I_{std} + \omega_s I_{stq} - \omega_s \frac{\mathrm{Sin}(\alpha + \theta_s)}{X_{sr}} V_{dc} + \frac{\omega_s}{X_{st}} V_s \mathrm{Cos}(\theta_s) \qquad (11)$$

$$\frac{\mathrm{d}I_{stq}}{\mathrm{d}t} = \frac{-\omega_s R_{st}}{X_{st}} I_{stq} + \omega_s I_{std} + \omega_s \frac{\mathrm{Cos}(\alpha + \theta_s)}{X_{sr}} V_{dc} + \frac{\omega_s}{X_{st}} V_s \sin(\theta_s) \qquad (12)$$

If LHS of Eqs. (11) and (12) are negative, the STATCOM is defined to be injecting else absorbing that axis current. The difference in the DC link capacitance voltage, there will be change in current flow in or from STATCOM as in Eq. (13).

$$\frac{\mathrm{d}V_{dc}}{\mathrm{d}t} = -\sqrt{3}\omega_s X_{dc} \mathrm{Sin}(\alpha + \theta_s) I_{std} - \sqrt{3}\omega_s X_{dc} \mathrm{Cos}(\alpha + \theta_s) I_{stq} \qquad (13)$$

The real and reactive power rating of STATCOM is decided by Eqs. (14)–(16) as

$$P_{st} + jQ_{st} = \frac{V_s V_{st} \mathrm{e}^{-j\alpha} - V_s^2}{R_{st} - jX_{st}} \qquad (14)$$

$$P_{st} = \frac{V_s V_{dc} R_{st} \mathrm{Cos}\alpha + V_s V_{dc} X_{st} \mathrm{Sin}\alpha - R_{st} V_s^2}{R_{st}^2 + X_{st}^2} \qquad (15)$$

$$Q_{st} = \frac{V_s V_{dc} X_{st} \mathrm{Cos}\alpha - V_s V_{dc} R_{st} \mathrm{Sin}\alpha - X_{st} V_s^2}{R_{st}^2 + X_{st}^2} \qquad (16)$$

Equations (11) and (12) are simplified as decoupling current and voltage parameters is represented in Eqs. (17) and (18)

$$\frac{\mathrm{d}I_{std}}{\mathrm{d}t} = -\frac{R_{st}}{L_{st}} I_{std} - \omega I_{stq} + \frac{1}{L_{st}}(V_{std} - V_{td}) \qquad (17)$$

$$\frac{\mathrm{d}I_{stq}}{\mathrm{d}t} = -\frac{R_{st}}{L_{st}} I_{stq} - \omega I_{std} + \frac{1}{L_{st}}\left(V_{stq} - V_{tq}\right) \qquad (18)$$

The current flow in the STATCOM d and q axis is described in Eqs. (1) and (2) with supply current constant as assumption are simplified with the operation under the steady-state and rewritten as in Eqs. (17) and (18).

3.3 Analytical Analysis of STATCOM Converter Capacitor

Based on Equations from 11 to 18, the STATCOM power flow equation in terms of capacitor voltage, terminal voltage and STATCOM voltage and current as in Eq. (19)

$$\frac{3}{2}\left[-V_{std}I_{std} - V_{std}I_{stq}\right] = CV_{dc}\frac{\mathrm{d}V_{dc}}{\mathrm{d}t} + \frac{V_{dc}^2}{R_{dc}} + \frac{3}{2}\left(V_{td}I_{d1} + V_{tq}I_{q1}\right) \tag{19}$$

And hence the change in dc link voltage across the capacitor is given by Eq. (20)

$$V_{dc} = \frac{3}{2CV_{dc}}\left[-V_{std}I_{std} - V_{stq}I_{stq} - V_{td}I_{d1} - V_{tq}I_{q1}\right] - \frac{V_{dc}}{CR_{dc}} \tag{20}$$

Hence, the d-axis STATCOM current as shown in Eq. (21) gives the relation with the difference in the STATCOM and the PCC terminal voltage and the current injected into it. If there is no difference in voltage, the current injected will be small.

$$\frac{\mathrm{d}I_{sd}}{\mathrm{d}t} = -\frac{R_s}{L_s}I_{ds} - \omega I_{qs} + \frac{1}{L}(V_s - V_{td}) \tag{21}$$

4 Design and Analysis of Controller Circuit of STATCOM

The PQ control theory based STATCOM controller is in Fig. 5 with the reference voltage and current parameters taken from bus number 10. The reference real and reactive powers are derived at bus 10 in three axis form as in Eqs. (22) and (23).
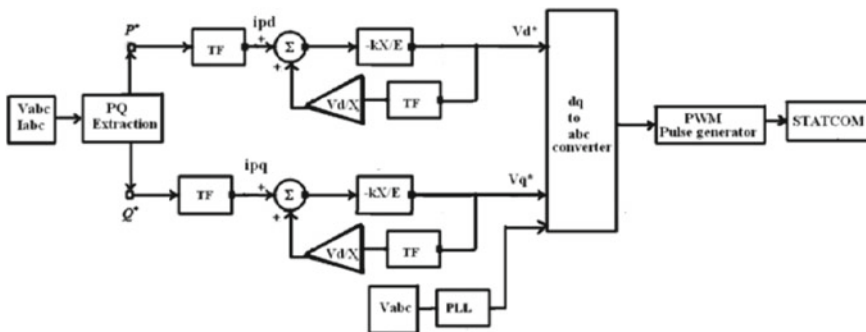
$$P = V_aI_a + V_bI_b + V_cI_c \tag{22}$$

Fig. 5 Block Diagram of STATCOM controller

$$Q = \frac{[(V_a - V_b)I_c + (V_b - V_c)I_a + (V_c - V_a)I_b]}{\sqrt{3}} \tag{23}$$

Powers are also extractable from stationary two axis parameters as in Eqs. (24) and (25) as

$$P = V_d I_d + V_q I_q \tag{24}$$

$$Q = V_q I_d - V_d I_q \tag{25}$$

Equations (24) and (25) is represented in the matrix notation as in Eqs. (26) and (27) as

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{26}$$

or

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{1}{V_d^2 + V_q^2} \begin{bmatrix} V_d & -V_q \\ V_q & V_d \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{27}$$

The voltages and the two powers P and Q in Eq. (27) are taken from the point where the STATCOM is connected, based on this equation the d and q axis current injections are obtained. Based on the requirement of real or reactive power, respective axis current flow parameter changes and will inject the current at the point of connection independently. The STATCOM bus voltage terminal point angle is given by 'α' refers and its phase angle measured by the PLL is represented as θ_s.

5 Time Domain Simulation

The test system shown in Fig. 1 is used for the analysis and the results are observed with STATCOM and with UPFC in two cases. Gen 1 and 2 represent generating stations in area 1 and Gen 3 and 4 in area 2. An equivalent nominal Π transmission line network is considered for analysis. The direct and quadrature axis currents will independently control the STATCOM real and the reactive power flow. The two phase to three phase voltage transformation by using inverse Park's transformation (dq to *abc*) and this reference voltage is fed to the STATCOM PWM converter. This PWM will control the current flow and the direction of STATCOM based on the voltage at reference terminal and at the STATCOM DC link capacitor terminal. If the voltage magnitude is higher at the reference point, the current will flow towards STATCOM capacitor terminal and will be charged otherwise, current flow from STATCOM to the reference injected point. The parameters values are specified in the Appendix at

the end of the conclusion section. Here, base voltage is 230 KV and the base current is 1600 A. The two case studies are discussed now:

5.1   Case-1: With STATCOM

The STATCOM connected two area power system for the test system shown in Fig. 1 is used here. A fault occurred at the bus 7 which is near the Area-1 and also the STATCOM is placed near this terminal. It is pragmatic from Fig. 6a (i) and (ii), the voltage and current in the area-2 is compensated completely, while in area-1 to a certain extent only due to the direction and location of fault and based on STATCOM reference point. In area-1, voltage dips from 1 to 0.45 p.u. and current raised from 0.5 to 0.95 p.u., whereas without STATCOM, the voltage dip is 0.1 p.u., and the and current rise is 18 p.u., (which is not shown here). Based on Fig. 6b (i) the voltage in q-axis in area-1 reached 0.85 p.u., during the fault and reached to normal pre-fault value once fault is cleared without any oscillations as they are damped effectively using the STATCOM. There is voltage dip or power oscillations observed in the area-2 as these are compensated successfully by the STATCOM. There are considerable oscillations in the real power in area-1 but are sustained and decreasing with time.

The area-2 synchronous generator (SG) parameters are shown in Fig. 6b (ii), the two dimensional voltages are almost constant during and after the fault and also no oscillations in the power are observed as these are efficiently mitigated by the STATCOM. The voltage at the STATCOM converter point and the current injected by it at bus number 7 is shown in Fig. 6c.

As the STATCOM behaves like a low impedance path when the current at the point of injection increases, will be diverted to its capacitor VSC terminal point and this current is reinjected to the same terminal, there by compensation is done effectively. This action will make sure, the surge current is decreased effectively in both the areas and mainly the area-2 as this is the reference point and the voltage being compensated during the fault. The post fault behaviour is also improved in both areas considerably.

5.2   Case-2: With UPFC

For the same test system, UPFC is placed in between buses 7 and 8. The advantage of UPFC over STATCOM is, it has both STATCOM and SSSC, which are shunt and series devices. The rating of system is higher than single STATCOM and hence has much higher and quicker capability to mitigate the voltage dip and power oscillations damping. SSSC is connected towards bus 7 and STATCOM in bus 8 in this study. Comparing Figs. 7a (i) and 6a (i), voltage compensation is higher with UPFC than STATCOM for Gen 1 in area 1. With UPFC the voltage decreased from 1 to 0.9 p.u., whereas with STATCOM, it is 0.5 p.u., but surge current is higher with UPFC. For
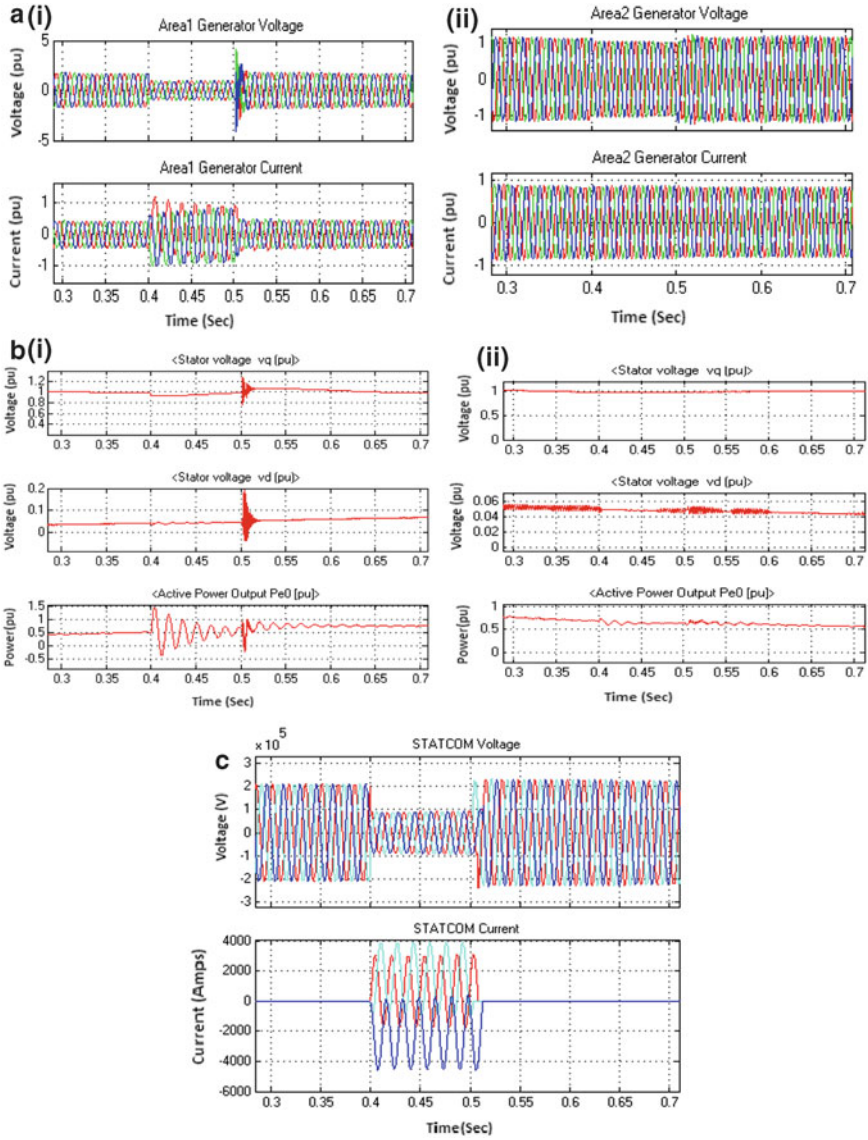
Fig. 6 **a** Terminal voltage and current in (i) area-1 (ii) in area2 with STATCOM connection. **b** SG parameters in (i) area-1 and (ii) in area2 using STATCOM converter. **c** STATCOM terminal Voltage and the current injection to the bus 7
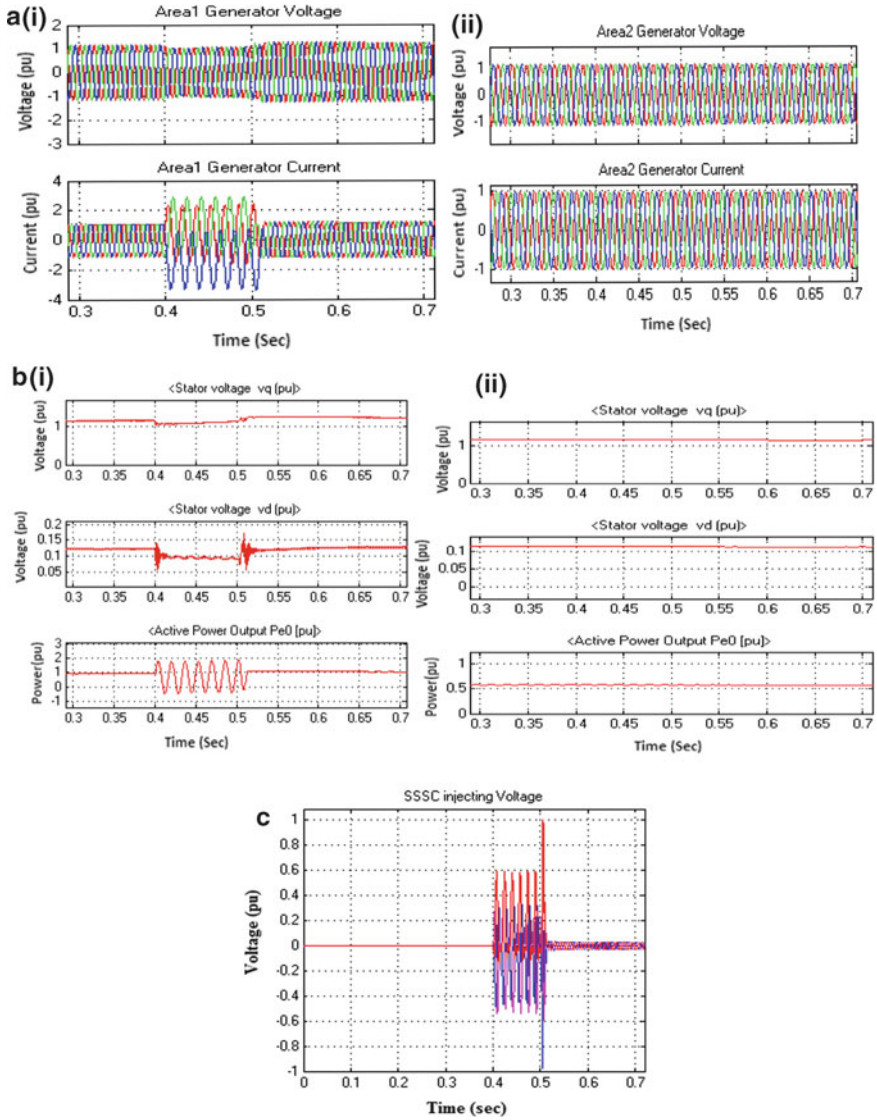
Fig. 7 **a** (i) Voltage and current in area 1 with UPFC (ii) Voltage and current in area 2 with UPFC. **b** (i) SG parameters in area 1 and the (ii) area 2 using UPFC based FACTS device. **c** DC voltage across capacitor link

area 2 shown in Fig. 7a (ii), the mitigation of voltage and current are same for both UPFC and STATCOM.

From Fig. 7b (i), the *q*-axis voltage decreased from 1 to 0.9 p.u. at the instant of fault and slowly regains to normal value even fault is not cleared. But when fault is cleared a surge voltage is produced due to sudden decrease in current flow and the oscillations were damped quickly due to UPFC. From Fig. 7b (ii), the system behaves normally with or without fault. The voltage injected by the SSSC during the fault is shown in Fig. 7c. It can be observed that voltage across capacitor is almost constant and can absorb huge inrush current entering into the circuit. But when fault is released voltage across capacitor is increased due to the influence of STATCOM.

However UPFC is an excellent device which can regulate power flow in the line, decrease losses, improve power factor, regulate voltage margin and can damp effectively power oscillations in the system. Disadvantages are design complexity, high capital investment for gate circuit, switches and high rating capacitors and transformer bank. If power oscillations can be damped quickly and mitigate voltage sag and limit surge current for UPFC, it can be a much better device.

6 Conclusion

A severe low impedance symmetrical ground fault occur in the midpoint of the two area Kundur system with four synchronous generators with two in each sides of two areas is considered. STATCOM is placed in area-1 and reference is taken in area-2. During this fault, the voltage in area-1 decreased to about half of its pre-fault value and area-2 voltage is almost constant with the STATCOM injection. The voltage dip or power oscillations are considerably very high when there is no STATCOM. It is also observed that voltage mitigation in area-1 is also improved using UPFC than with STATCOM. The power oscillations in both areas are efficiently damped, the *q*-axis voltage is maintained almost pre-fault value even during and after the fault using UPFC. Therefore, the STATCOM is better shunt device than other basic shunt FACTS devices, but UPFC as it is having both series and shunt compensating devices like STATCOM and SSSC, it is superior in performance. The advantages of proposed STATCOM controller are its simplicity in design and are applicable. In the controller, no decoupling components, hence so system parameters effect and dependency are minimised. No need to calculate voltage across DC link capacitance, but STATCOM three phase voltages and current parameter is required. The cost incurred to design is much cheaper than UPFC and complexity of designing series and shunt compensators can be eliminated. It is more effective than UPFC in voltage regulation, power factor correction and oscillations damping.

Appendix

Synchronous generator and its transformer: Nominal Power- 200 MW, nominal phase to phase voltage-13800 V, frequency-60 Hz, Xd-1.315, $Xd^1 = 0.286$, $Xd^{11} = 0.262$, $Xq = 0.484$, $Xq^1 = 0.253$, $Xq^{11} = 0.178$. Transformer nominal power rating 210 MW, voltage rating- 13.8/230 KV, internal resistance and reactance are 0.0027 and 0.08 per-unit.

Transmission line parameters: Nominal PI transmission line network is considered. Positive and zero sequence resistance is 0.01273 and 0.3864 ohms per kilometre.

STATCOM Parameters: Three winding, three phase transformer, 120 MVA, 230/230/20 KV for single STATCOM and 60 MVA, 230/230/20 KV.

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