Chapter 6

RESULTS AND DISCUSSION

6.0 Test systems

Single line diagrams and SIMULINK models of the two test systems are given in chapter-2. Fig. 2.9 and 2.10 for 3-Machine 9-Bus WSCC power system and Fig. 2.11 and 2.12 for 6-Machine 30-Bus IEEE test power system of the two test systems.

6.1 3-Machine 9-Bus WSCC power system

6.1.1 Presence of SVC in 3-Machine 9-Bus WSCC power System

The SVC is placed at the bus-5 in 3-Machine 9-Bus WSCC power system as determined in the chapter-2. The dynamic performance of SVC with a step variation of \(V_{ref} = [1 0.9 1.1 1]\) at time \(t = [0 5 10 15]\) is shown in Fig.6.1.

For transient stability analysis 3-Ph short circuit fault at bus –7 at time \(t = 1\)sec and cleared at \(t = 1.1\)sec is considered.

Fig.6.1 (a) Voltage response
6.1.1.1 **Rotor angle oscillations**

The Fig. 6.2 and 6.3 shows the rotor angle oscillations of generator-2 and generator-3 with respect to generator-1 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. The fault exists for the duration of 0.1 sec. These plots show the rotor angle oscillations with and without the presence of the SVC in the system. It is obvious from these Figures that SVC with proposed controller (SVC equipped with FLCPOD along with PIVC) is damping the oscillations considerably
Fig. 6.2. Rotor angle Oscillations of Generator – 2 with respect to Generator – 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of SVC

Fig. 6.3. Rotor angle Oscillations of Generator – 3 with respect to Generator – 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of SVC

6.1.1.2 Power oscillations

The Fig. 6.4, Fig. 6.5 and Fig. 6.6 show the power oscillations of generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC
power system for 3–Phase short circuit fault at bus – 7. It is clear
from these Figures that SVC with proposed controller is damping the
power oscillations effectively.

**Fig.6.4** Oscillations in Power output of Generator 1 for 3-Ph Short
circuit at Bus – 7 in 3 – Machine 9 – Bus WSCC power system with
the presence of SVC

**Fig.6.5** Oscillations in Power output of Generator 2 for 3-Ph Short
circuit at Bus – 7 in 3 – Machine 9 – Bus WSCC power system with
the presence of SVC
Fig. 6.6 Oscillations in Power output of Generator 3 for 3-Ph Short circuit at Bus – 7 in 3 – Machine 9 – Bus WSCC power system with the presence of SVC

6.1.1.3 Angular speeds

The Fig. 6.7, Fig. 6.8 and Fig. 6.9 show the angular speeds of generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. These plots also compare the speed (rad/sec) variation with and without SVC in the system. Without SVC, it is taking more than 10 seconds to reach final steady value. Whereas as with SVC in the system, oscillations settle down to final steady value in less than 10 sec but initially there is large variation in the speed. SVC with proposed controller shows better performance.
Fig. 6.7 Speed Variation of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3 - Machine 9 – BusWSCC power system with the presence of SVC

Fig. 6.8 Speed Variation of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3 - Machine 9 – BusWSCC power system with the presence of SVC
Fig. 6.9 Speed Variation of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3 – Machine 9 – BusWSCC power system with the presence of SVC

6.1.1.4 Voltage profile at SVC bus

The Fig. 6.10 shows the voltage variation at bus-5 at which SVC is connected in 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. With SVC in the system, voltage settles to final steady value in around 8 sec otherwise it is taking more than 10 sec.

Fig. 6.10 Voltage at bus – 5 for 3-Ph Short-circuit at Bus – 7 in 3- Machine 9-Bus WSCC Power system with the presence of SVC
6.1.1.5 Susceptance of SVC

The Fig.6.11 shows the susceptance variation of SVC for 3–Phase short circuit fault at bus – 7 in 3-Machine 9-BusWSCC power system with SVC is located at bus – 5. SVC susceptance reaches steady value in around 8 sec; this time indicates oscillations damping time in the system.

![Graph showing susceptance variation of SVC](image)

**Fig.6.11** Susceptance variation of SVC for 3–Phase short circuit fault at bus – 7 in 3–Machine 9 – Bus WSCC power system with SVC is located at bus – 5.

6.1.2 Presence of STATCOM in 3-Machine 9-Bus WSCC power system

The STATCOM is placed at the bus-5 in 3-Machine 9-Bus WSCC power system as determined in the capter-2. The dynamic performance of STATCOM with a step variation of $V_{ref} = [1 \ 0.9 \ 1.1 \ 1]$ at time $t = [0 \ 5 \ 10 \ 15]$ is shown in Fig.6.12.

For transient stability analysis 3-Ph short circuit fault at bus –7 at time $t = 1$sec and cleared at $t = 1.1$sec is considered.
Fig. 6.12 (a) Voltage response

Fig. 6.12 (b) Reactive current of STATCOM

Fig. 6.12 STATCOM dynamic response at bus – 5 in 3-Machine 9-Bus WSCC power system

6.1.2.1 Rotor angle oscillations

The Fig. 6.13 and Fig. 6.134 shows the rotor angle oscillations of generator-2 and generator-3 with respect to generator-1 of 3-Machine 9-Bus WSCC power system for 3-phase short circuit fault at bus – 7. The fault exists for the duration of 0.1 sec. These plots show the rotor angle oscillations with and without the presence of the STATCOM in
the system. It is obvious from these Figures that STATCOM with proposed controller (STATCOM equipped with FLCPOD along with PIVC) is damping the oscillations considerably.

**Fig.6.13**  Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-BusWSCC power system with the presence of STATCOM

**Fig.6.14**  Rotor angle Oscillations of Generator 3 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-BusWSCC power system with the presence of STATCOM
6.1.2.2 Power oscillations

The Fig.6.15, Fig.6.16 and Fig.6.17 show the power oscillations of generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. It is clear from these Figures that STATCOM with proposed controller is damping the power oscillations effectively.

**Fig.6.15** Oscillations in Power output of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of STATCOM

**Fig.6.16** Oscillations in Power output of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of STATCOM
6.1.2.3 Angular speeds

The Fig.6.18, Fig.6.19 and Fig.6.20 show the angular speeds of generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. These plots also compare the speed (rad/sec) variation with and without STATCOM in the system. Without STATCOM, it takes more than 10 seconds to reach final steady value. Whereas as with STATCOM in the system, oscillations settle down to final steady value in less than 10 sec but initially there is a large variation in the speed. STATCOM with proposed controller shows better performance.
Fig. 6.18  Speed Variation of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-BusWSCC power system with the presence of STATCOM

Fig. 6.19  Speed Variation of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of STATCOM
Fig. 6.20  Speed Variation of Generator 3 for 3-Ph Short circuit at Bus – 7 in 3- Machine 9-BusWSCC power system with the presence of STATCOM

6.1.2.4  Voltage profile at STATCOM bus

The Fig. 6.21 shows the voltage variation at bus-5 at which STATCOM is connected in 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. With STATCOM in the system, voltage settles to final steady value in around 8 sec otherwise it is taking more than 10 sec.

Fig. 6.21  Voltage at bus – 5 for 3-Ph Short-circuit at Bus – 7 in 3- Machine 9-Bus WSCC Power system with the presence of STATCOM
6.1.2.5 Reactive current of STATCOM

The Fig.6.22 shows the reactive current variation of STATCOM for 3-phase short circuit fault at bus 7 in 3-Machine 9-Bus WSCC power system with STATCOM is located at bus 5. STATCOM reactive current reaches steady value in around 8 sec; this time indicates oscillations damping time in the system.

**Fig.6.22** Reactive current variation of STATCOM for 3-phase short circuit fault at bus 7 in 3-Machine 9-Bus WSCC power system with STATCOM is located at bus 5.

6.1.3 Presence of TCSC in 3-Machine 9-Bus WSCC power system

The TCSC is placed in transmission line 7-5 in 3-Machine 9-Bus WSCC power system as determined in the capter-2 by Extended Phasor Voltage Analysis is simulated. The dynamic performance of TCSC with a step variation of Pref = [100 110 100] at time t = [5 15 25] is shown in Fig.6. 32. Up to t = 5sec TCSC is bypassed so actual power flow in the line i.e., 84.19MW.
For transient stability analysis 3-Ph short circuit fault at bus -7 at time $t = 1\sec$ and cleared at $t = 1.1\sec$ is considered and TCSC is bypassed up to $t = 0.5\sec$.

**Fig.6.23** (a) Power flow in line 7–5

**Fig.6.23** (b) $X_{\text{tcsc}}$ of TCSC

**Fig.6.23** TCSC dynamic response in line 7–5 in 3-Machine 9-Bus WSCC power system

### 6.1.3.1 Rotor angle oscillations

The Fig.6.24 and Fig.6.25 shows the rotor angle oscillations of generator-2 and generator-3 with respect to generator-1 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7.
The fault exists for the duration of 0.1 sec. These plots show the rotor angle oscillations with and without the presence of the TCSC in the system. It is obvious from these Figures that TCSC with proposed controller (TCSC equipped with FLCPOD along with PIPFC) is damping the oscillations considerably.

**Fig.6.24** Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-BusWSCC power system with the presence of TCSC

**Fig.6.25** Rotor angle Oscillations of Generator 3 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of TCSC
6.1.3.2 Power oscillations

The Fig.6.26, Fig.6.27, Fig.6.28 and Fig.6.29 show the power oscillations of generator-1, generator-2, generator-3 and power variation through transmission line 7-5 of 3-Machine 9-BusWSCC power system for 3–Phase short circuit fault at bus – 7.

From these Figures, Without TCSC the power oscillations take more than 10sec to settling down. TCSC with proposed controller in the system power oscillations settle down to final steady value in less than 5 sec. TCSC with proposed controller damps the power oscillations effectively.

Fig.6.26 Oscillations in Power output of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of TCSC
Fig.6.27  Oscillations in Power output of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of TCSC

Fig.6.28  Oscillations in Power output of Generator 3 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of TCSC
6.1.3.3 Angular speeds

The Fig.6.30, Fig.6.31 and Fig.6.32 show the angular speeds of generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. These plots also compare the speed (rad/sec) variation with and without TCSC in the system. Without TCSC, it takes more than 10 seconds to reach final steady value. Whereas as with TCSC in the system oscillations settle down to final steady value in less than 5 sec. TCSC with proposed controller shows better performance.
Fig. 6.30  Speed Variation of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of TCSC

Fig. 6.31  Speed Variation of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3- Machine 9-Bus WSCC power system with the presence of TCSC
Fig.6.32  Speed Variation of Generator 3 for 3-Ph Short circuit at Bus – 7 in 3- Machine 9-Bus WSCC power system with the presence of TCSC

6.1.3.4  Voltage profile at input and output terminals of TCSC

The Fig.6.33 and Fig.6.34 shows the voltage variation at input and output terminals of TCSC which is connected in the line 7 –5 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. With TCSC in the system, voltage settles to final steady value in around 5 sec otherwise it takes more than 10 sec.

Fig.6.33  Voltage at input terminals of TCSC for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of TCSC in the line 7 –5.
**Fig. 6.34** Voltage at bus – 5 for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC Power system with the presence of TCSC in the line 7 – 5.

### 6.1.3.5 $X_{TCSC}$ of TCSC

The Fig. 6.35 shows the reactance of TCSC for 3 – Phase short circuit fault at bus – 7 in 3-Machine 9-Bus WSCC power system with TCSC is placed in the line 7 – 5. TCSC reactance reaches steady value in around 5 sec with proposed controller; it is around 8sec with PIPFC only. This indicates the proposed controller shows better performance.

**Fig. 6.35** Reactance of TCSC for 3 – Phase short circuit fault at bus – 7 in 3-Machine 9-Bus WSCC power system with TCSC is placed in the line 7 – 5.
6.1.4 Presence of SSSC in 3-Machine 9-Bus WSCC power system

The SSSC is placed in transmission line 7 –5 in 3-Machine 9-Bus WSCC power system as determined in the capter-2 by Extended Phasor Voltage Analysis is simulated. The dynamic performance of SSSC with a step variation of Pref = [0.5 1 0.5] pu at time t = [5 15 25] is shown in Fig.6.36. Up to t = 5sec SSSC is bypassed so actual power flow in the line i.e., 0.8419 pu.

For transient stability analysis 3-Ph short circuit fault at bus –7 at time t = 1sec and cleared at t = 1.1sec is considered and SSSC is bypassed up to t = 0.5sec.

Fig.6.36 (a) Power flow in line 7 – 5

Fig.6.36 (b) Series injected reactive voltage of SSSC

Fig.6.36 SSSC dynamic response in line 7 –5 in 3-Machine 9-Bus WSCC power system
6.1.4.1 Rotor angle oscillations

The Fig.6.37 and Fig.6.38 shows the rotor angle oscillations of generator-2 and generator-3 with respect to generator-1 of 3-Machine 9-BusWSCC power system for 3 – Phase short circuit fault at bus – 7. The fault exists for the duration of 0.1 sec. These plots show the rotor angle oscillations with and without the presence of the SSSC in the system. It is obvious from these Figures that SSSC with proposed controller (SSSC equipped with FLCPOD along with PIPFC) damps the oscillations considerably.

![Fig.6.37](image_url)

**Fig.6.37** Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of SSSC
Fig.6.38  Rotor angle Oscillations of Generator 3 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-BusWSCC power system with the presence of SSSC

6.1.4.2  Power oscillations

The Fig.6.39, Fig.6.40, Fig.6.41 and Fig.6.42 show the power oscillations of generator-1, generator-2, generator-3 and power variation through transmission line 7-5 of 3-Machine 9-Bus WSCC power system for 3 –Phase short circuit fault at bus – 7.

From these Figures, Without SSSC the power oscillations take more than 10sec to settling down. SSSC with proposed controller in the system power oscillations settle down to final steady value in less than 5 sec. SSSC with proposed controller damps the power oscillations effectively.
Fig. 6.39 Oscillations in Power output of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-BusWSCC power system with the presence of SSSC

Fig. 6.40 Oscillations in Power output of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of SSSC
Fig. 6.41  Oscillations in Power output of Generator 3 for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-BusWSCC power system with the presence of SSSC

Fig. 6.42  Oscillations in Power through the line 7 – 5 for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of SSSC

6.1.4.3   Angular speeds

The Fig. 6.43, Fig. 6.44 and Fig. 6.45 show the angular speeds of generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. These plots
also compare the speed (rad/sec) variation with and without SSSC in the system. Without SSSC, it takes more than 10 seconds to reach final steady value. Whereas as with SSSC in the system oscillations settle down to final steady value in less than 5 sec. SSSC with proposed controller shows better performance.

**Fig.6.43** Speed Variation of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3- Machine 9-Bus WSCC power system with the presence of SSSC

**Fig.6.44** Speed Variation of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3- Machine 9-Bus WSCC power system with the presence of SSSC
Fig.6.45 Speed Variation of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3- Machine 9-Bus WSCC power system with the presence of SSSC

6.1.4.4 Voltage profile at input and output terminals of SSSC

The Fig.6.46 and Fig.6.47 shows the voltage variation at input and output terminals of SSSC which is connected in the line 7 –5 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. With SSSC in the system, voltage settles to final steady value in around 5 sec otherwise it takes more than 10 sec.

Fig.6.46 Voltage at input terminals of SSSC for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of SSSC in the line 7 –5.
6.1.4.5 Series injected voltage $V_q$ of SSSC

The Fig.6.48 shows the series injected voltage of SSSC for 3-Phase short circuit fault at bus – 7 in 3-Machine 9-Bus WSCC power system with SSSC placed in the line 7–5. Series injected voltage of SSSC reaches steady value in around 7sec with proposed controller; it is around 9sec with PIPFC only. This indicates the proposed controller shows better performance.
6.1.5 Presence of UPFC in 3-Machine 9-Bus WSCC power system

The UPFC is placed in transmission line 7–5 in 3-Machine 9-Bus WSCC power system as determined in the chapter-2 by Extended Phasor Voltage Analysis is simulated. The dynamic performance of UPFC with a step variation of Pref = [1 1.1 1] pu at time t = [0 15 25] at Vref = 1pu is shown in Fig.6.49. Up to t = 1sec UPFC series element is bypassed so actual power flow in the line i.e., 0.8419 pu.

For transient stability analysis 3-Ph short circuit fault at bus –7 at time t = 1sec and cleared at t = 1.1sec is considered and UPFC series element is bypassed up to t = 0.5sec.

![Fig.6.49 (a) Power flow in the line 7–5](image1)

![Fig.6.49 (b) Voltage at Bus – 5](image2)

**Fig.6.49** UPFC dynamic response in line 7–5 in 3-Machine 9-Bus WSCC power system
6.1.5.1 Rotor angle oscillations

The Fig.6.50 and Fig.6.51 shows the rotor angle oscillations of generator-2 and generator-3 with respect to generator-1 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. The fault exists for the duration of 0.1 sec. These plots show the rotor angle oscillations with and without the presence of the UPFC in the system. It is obvious from these Figures that UPFC with proposed controller (UPFC equipped with FLCPOD along with PI controller) damps the oscillations considerably.

![Fig.6.50](image)

**Fig.6.50** Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC
The Fig.6.52, Fig.6.53, Fig.6.54 and Fig.6.55 show the power oscillations of generator-1, generator-2, generator-3 and power variation through transmission line 7-5 of 3-Machine 9-Bus WSCC power system for 3–Phase short circuit fault at bus – 7.

From these Figures, Without UPFC the power oscillations take more than 10sec to settling down. UPFC with proposed controller in the system power oscillations settle down to final steady value in less than 7 sec. UPFC with proposed controller damps the power oscillations effectively.

**Fig.6.51** Rotor angle Oscillations of Generator 3 with respect to Generator 1 for 3-Ph Short circuit at bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC

**6.1.5.2 Power oscillations**

The Fig.6.52, Fig.6.53, Fig.6.54 and Fig.6.55 show the power oscillations of generator-1, generator-2, generator-3 and power variation through transmission line 7-5 of 3-Machine 9-Bus WSCC power system for 3–Phase short circuit fault at bus – 7.

From these Figures, Without UPFC the power oscillations take more than 10sec to settling down. UPFC with proposed controller in the system power oscillations settle down to final steady value in less than 7 sec. UPFC with proposed controller damps the power oscillations effectively.
Fig. 6.52  Oscillations in Power output of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC

Fig. 6.53  Oscillations in Power output of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC
Fig.6.54 Oscillations in Power output of Generator 3 for 3-Ph Short
circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the
presence of UPFC

Fig.6.55 Oscillations in Power through the line 7 – 5 for 3-Ph
Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with
the presence of UPFC

6.1.5.3 Angular speeds

The Fig.6.56, Fig.6.57 and Fig.6.58 show the angular speeds of
generator-1, generator-2 and generator-3 of 3-Machine 9-Bus WSCC
power system for 3 – Phase short circuit fault at bus – 7. These plots
also compare the speed (rad/sec) variation with and without UPFC in the system. Without UPFC, it takes around 9 seconds to reach final steady value. Whereas as with UPFC in the system oscillations settle down to final steady value in around 6 sec. UPFC with proposed controller shows better performance.

**Fig.6.56** Speed Variation of Generator 1 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC

**Fig.6.57** Speed Variation of Generator 2 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC
Fig. 6.58 Speed Variation of Generator 3 for 3-Ph Short circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC

6.1.5.4 Voltage profile at input and output terminals of UPFC

The Fig. 6.59 and Fig. 6.60 shows the voltage variation at input and output terminals of UPFC which is connected in the line 7 – 5 of 3-Machine 9-Bus WSCC power system for 3 – Phase short circuit fault at bus – 7. With UPFC in the system, voltage settles to final steady value in around 5 sec otherwise it takes more than 10 sec.

Fig. 6.59 Voltage at input terminals of UPFC for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC in the line 7 – 5.
Voltage at bus – 5 for 3-Ph Short-circuit at Bus – 7 in 3-Machine 9-Bus WSCC power system with the presence of UPFC in the line 7–5.

6.1.5.5 Reactive current of shunt converter

The Fig.6.61 shows the reactive current of shunt converter of UPFC for 3 – Phase short circuit fault at bus – 7 in 3-Machine 9-Bus WSCC power system with UPFC is placed in the line 7–5. Shunt reactive current of UPFC reaches steady value in around 5 sec with proposed controller; it is around 7sec with PI controller only. This indicates the proposed controller shows better performance.
6.1.5.6 **Series injected voltage** $V_q$ **of Series converter**

The Fig.6.62 shows the reactive current of shunt converter of UPFC for 3 – Phase short circuit fault at bus – 7 in 3-Machine 9-BusWSCC power system with UPFC is placed in the line 7 – 5. Series injected voltage of UPFC reaches steady value in around 5 sec with proposed controller; it is around 7sec with PI controller only. This indicates the proposed controller shows better performance.

![Fig.6.62 Series injected voltage of UPFC for 3 – Phase short circuit fault at bus – 7 in 3-Machine 9-Bus WSCC power system with UPFC is placed in the line 7 – 5.](image)

6.2 **6-Machine 30-Bus IEEE power system**

Consider SIMULINK model of 6-Machine 30-Bus IEEE power system as shown in Fig.2.10 with all FACTS devices as considered in 3 –Machine 9 – Bus WSCC power system. Observe the dynamic performance of the devices and rotor angle oscillations during fault conditions through the simulation of the system.
6.2.1 Presence of SVC in 6-Machine 30-Bus IEEE power System

The SVC is placed at the bus-7 in 6-Machine 30-Bus IEEE power system as determined in the chapter-2. The dynamic performance of SVC with a step variation of $V_{ref} = [1 \ 1.05 \ 1 \ 0.95 \ 1]$ pu at time $t = [0 \ 1 \ 2 \ 3 \ 4]$ sec. is shown in Fig.6.63.

For transient stability analysis 3-Ph short circuit fault at bus –1 at time $t = 1$sec and cleared at $t = 1.15$sec is considered.

![Fig.6.63](image)

**Fig.6.63** SVC dynamic response at bus – 7 in 6-Machine 30-Bus IEEE power system.

6.2.1.1 Rotor angle oscillations

The rotor angle oscillations of generator-2 with respect to generator-1 of 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1 is shown in Fig.6.64. The fault exists for the duration of $0.15$ sec. These plots show the rotor angle oscillations with and without the presence of the SVC in the system. It is obvious from these Figures that SVC with proposed controller (SVC equipped with FLCPOD along with PIVC) damps the oscillations effectively.
Fig. 6.64. Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence of SVC

6.2.1.2 Voltage profile at SVC bus

The voltage variation at bus-7 at which SVC is connected in 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1 is shown in Fig.6.65. With SVC in the system, voltage settling time is less when compared with without SVC in the system but large variation in initial position.
Fig.6.65  Voltage at bus – 7 for 3-Ph Short-circuit at Bus – 1 in 6-Machine 30-Bus IEEE Power system with the presence of SVC

6.2.1.3  Susceptance of SVC

The susceptance variation of SVC for 3 - Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with SVC is located at bus – 7 is shown in Fig.6.66. SVC susceptance reaches steady value in around 3.5sec; this time indicates oscillations damping time in the system.

Fig.6.66  Susceptance variation of SVC for 3 - Phase short circuit fault at bus – 1 in 6 – Machine 30 – Bus IEEE power system with SVC is located at bus – 7.

6.2.2 Presence of STATCOM in 6-Machine 30-Bus IEEE power system

The STATCOM is placed at the bus-7 in 6-Machine 30-Bus IEEE power system as determined in the chapter-2. The dynamic performance of STATCOM with a step variation of $V_{ref} = [1 1.05 1 0.95 1]$ pu at time $t = [0 1 2 3 4]$ sec. is shown in Fig.6.67.
For transient stability analysis 3-Ph short circuit fault at bus –1 at time t = 1sec and cleared at t = 1.15sec is considered.

![Graph](image1.png)

**Fig.6.66** STATCOM dynamic response at bus – 7 in 6-Machine 30-Bus IEEE power system

### 6.2.2.1 Rotor angle oscillations

The rotor angle oscillations of generator-2 with respect to generator-1 of 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1 is shown in Fig.6.67. The fault exists for the duration of 0.15 sec. These plots show the rotor angle oscillations with and without the presence of the STATCOM in the system. It is obvious from these Figures that STATCOM with proposed controller (STATCOM equipped with FLCPOD along with PIVC) damps the oscillations effectively.

![Graph](image2.png)
**Fig.6.67**  Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence of STATCOM

**6.2.2.2  Voltage profile at STATCOM bus**

The voltage variation at bus-7 at which SVC is connected in 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1is shown in Fig.6.68. With SVC in the system, voltage is settling time is less when compared with without STATCOM in the system but large variation in initial position

**Fig.6.68**  Voltage at bus – 7 for 3-Ph Short-circuit at Bus – 1 in 6-Machine 30-Bus IEEE Power system with the presence of STATCOM

**6.2.2.3  Reactive current of STATCOM**

The reactive current of STATCOM for 3 – Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with STATCOM is located at bus – 7is shown in Fig.6.69. Form these plots;
it shows that STACOM is effectively utilized during oscillations with proposed controller.

![Fig.6.69](image)

**Fig.6.69** Reactive current variation of STATCOM for 3–Phase short circuit fault at bus 1 in 6-Machine 30-Bus IEEE power system with STATCOM is located at bus – 7.

### 6.2.3 Presence of TCSC 6-Machine 30-Bus IEEE power system

The TCSC is placed in transmission line 2–5 in 6-Machine 30-Bus IEEE power system as determined in the chapter-2 by Extended Phasor Voltage Analysis is simulated. The dynamic performance of TCSC with a step variation of $P_{ref} = [100 \ 110 \ 115 \ 110 \ 100]$ MW at time $t = [0 \ 5 \ 10 \ 15 \ 20]$ sec is shown in Fig.6.70. Up to $t = 1$ sec TCSC is bypassed so actual power flow in the line i.e., 78.8 MW.
For transient stability analysis 3-Ph short circuit fault at bus –1 at time $t = 1$sec and cleared at $t = 1.15$sec is considered and TCSC is bypassed up to $t = 0.5$sec.

**Fig.6.70** TCSC dynamic response in line 2 –5 in 6-Machine 30-Bus IEEE power system

### 6.2.3.1 Rotor angle oscillations

The rotor angle oscillations of generator-2 with respect to generator-1 of 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1is shown in Fig.6.71. The fault exists for the duration of 0.15 sec. These plots show the rotor angle oscillations with and without the presence of the TCSC in the system. From these
figures it is cleared that TCSC with proposed controller (TCSC equipped with FLCPOD along with PIPFC) damps the oscillations considerably

\[ \text{Fig.6.71} \quad \text{Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus WSCC power system with the presence of TCSC} \]

6.2.3.2 \( X_{\text{TCSC}} \) of TCSC

The reactance of TCSC for 3 – Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with TCSC is placed in the line 2 –5 is shown in Fig.6.72. Form these plots; it shows that TCSC is effectively utilized during oscillations with proposed controller.
Fig.6.72 Reactance of TCSC for 3 – Phase short circuit fault at bus – 1 in 6-Machine 30-Bus WSCC power system with TCSC is placed in the line 2 – 5.

6.2.4 Presence of SSSC in 6-Machine 30-Bus IEEE power system

The SSSC is placed in transmission line 2 – 5 in 6-Machine 30-Bus IEEE power system as determined in the chapter-2 by Extended Phasor Voltage Analysis is simulated. The dynamic performance of TCSC with a step variation of Pref = [0.5 0.75 1 1.15 1] MW at time t = [0 5 10 15 20] sec is shown in Fig.6.73. Up to t = 0.5sec SSSC is bypassed so actual power flow in the line i.e., 0.788 pu.

For transient stability analysis 3-Ph short circuit fault at bus – 1 at time t = 1sec and cleared at t = 1.15sec is considered and SSSC is bypassed up to t = 0.5sec.
6.2.4.1 **Rotor angle oscillations**

The rotor angle oscillations of generator-2 with respect to generator-1 of 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1 is shown in Fig.6.74. The fault exists for the duration of 0.15 sec. These plots show the rotor angle oscillations with and without the presence of the TCSC in the system. From these figures it is clear that TCSC with proposed controller (TCSC equipped with FLCPOD along with PIPFC) damps the oscillations considerably.
6.2.4.2 Series injected voltage $V_q$ of SSSC

Series injected reactive voltage of SSSC for 3-Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with SSSC is placed in the line 2–5 is shown in Fig.6.75. Form these plots; it shows that SSSC is effectively utilized during oscillations with proposed controller.
6.2.5 Presence of UPFC in 6-Machine 30-Bus IEEE power system

The UPFC is placed in transmission line 2–5 in 6-Machine 30-Bus IEEE power system as determined in the chapter-2 by Extended Phasor Voltage Analysis is simulated. The dynamic performance of UPFC with a step variation of $\text{Pref} = [1 1.1 1]$ pu at time $t = [0 15 25]$ sec with $V_{\text{ref}} = 1$pu is shown in Fig.6.76. Up to $t = 0.5$sec UPFC series element is bypassed so actual power flow in the line i.e., 0.788 pu.

For transient stability analysis 3-Ph short circuit fault at bus –1 at time $t = 1$sec and cleared at $t = 1.15$sec is considered and UPFC series element is bypassed up to $t = 0.5$sec.
Rotor angle oscillations

The rotor angle oscillations of generator-2 with respect to generator-1 of 6-Machine 30-Bus IEEE power system for 3 – Phase short circuit fault at bus – 1 is shown in Fig.6.77. The fault exists for the duration of 0.15 sec. These plots show the rotor angle oscillations with and without the presence of the UPFC in the system. It is obvious from these Figures that UPFC with proposed controller (UPFC equipped with FLCPOD along with PI controller) damps the oscillations considerably.
Fig.6.77  Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence of UPFC

6.2.5.2  Reactive current of shunt converter

Reactive current of shunt converter of UPFC for 3 – Phase short circuit fault at bus – 1 in 6 – Machine 30 – Bus IEEE power system with UPFC is placed in the line 2 – 5 is shown in Fig.6.78. From these plots; it shows that UPFC shunt element is effectively utilized during oscillations with proposed controller.

Fig.6.78  shunt reactive current of UPFC for 3 – Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with UPFC is placed in the line 2 – 5.
6.2.5.3 Series injected voltage $V_q$ of Series converter

Series injected Reactive Voltage of series converter of UPFC for 3 – Phase short circuit fault at bus – 1 in 6 – Machine 30 – Bus IEEE power system with UPFC is placed in the line 2 – 5 is shown in Fig.6.79. From these plots; it shows that UPFC series element is effectively utilized during oscillations with proposed controller.

![Series injected voltage of UPFC for 3 – Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with UPFC is placed in the line 2 – 5.]

**Fig.6.79** Series injected voltage of UPFC for 3 – Phase short circuit fault at bus – 1 in 6-Machine 30-Bus IEEE power system with UPFC is placed in the line 2 – 5.

6.2.6 Comparison of all FACTS devices (SVC, STATCOM, TCSC, SSSSC and UPFC) in 6-Machine 30-Bus IEEE power system

6.2.6.1 Rotor angle oscillations

Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers is shown in
Fig. 6.80. The fault exists for the duration of 0.15 sec. It is observed from these plots that series FACTS devices (TCSC, SSSC and UPFC) effectively damps rotor angle oscillations with compare shunt FACTS devices (SVC and STATCOM). UPFC with proposed controller (UPFC equipped with FLCPOD along with PI controller) damps the rotor angle oscillations considerably by simultaneous operation of shunt and series converters.

**Fig. 6.80** Rotor angle Oscillations of Generator 2 with respect to Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers

### 6.2.6.2 Power oscillations

Power oscillations of Generator 1 and Generator 2 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with
the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers is shown in Fig.6.81 and Fig. 6.82 respectively. The fault exists for the duration of 0.15 sec. It is observed from these plots that series FACTS devices (TCSC, SSSC and UPFC) effectively damps power oscillations with compare shunt FACTS devices (SVC and STATCOM). UPFC with proposed controller (UPFC equipped with FLCPOD along with PI controller) damps the power oscillations considerably by simultaneous operation of shunt and series converters.

**Fig. 6.81** Power output Oscillations of Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers
6.2.6.3 Angular speeds

Angular speeds of Generator 1 and Generator 2 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers is shown in Fig. 6.83 and Fig. 6.84 respectively. The fault exists for the duration of 0.15 sec. It is observed from these plots all FACTS devices (SVC, STATCOM, TCSC, SSSC and UPFC) give almost same settling time. But, with shunt FACTS devices (SVC and STATCOM) first peak in speed oscillation is considerably reduced when compare with series FACTS devices (TCSC, SSSC and UPFC).
**Fig. 6.83** Speed Variation of Generator 1 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers

**Fig. 6.84** Speed Variation of Generator 2 for 3-Ph Short circuit at bus – 1 in 6-Machine 30-Bus IEEE power system with the presence FACTS devices SVC, STATCOM, TCSC, SSSC and UPFC alone with proposed controllers
6.4 Summary

In this chapter, the improvement of the voltage profile, damping of rotor angle oscillations, damping of power oscillations and speed responses by incorporating the SVC, STATCOM, TCSC, SSSC and UPFC is discussed. It can be observed from the simulation results the UPFC is gives better performance in all aspects.