

IMPROVEMENT OF TRANSIENT STABILITY OF POWER SYSTEM BY IPFC, SSSC AND STATCOM

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Abstract – Power engineers are currently facing challenges to increase the power transfer capabilities of existing transmission system. Flexible AC Transmission system (FACTS) controllers can balance the power flow and thereby use the existing power system network most efficiently. Because of their fast response, FACTS controllers can also improve the stability of an electrical power system by helping critically disturbed generators to give away the excess energy gained through the acceleration during fault.

This paper examines the influence of three FACTS controllers such as Interline Power Flow Controller (IPFC), Static Synchronous Series Compensator (SSSC) and STATIC synchronous COMPensator (STATCOM) on the synchronizing power and damping power of a single-machine infinite bus system. The main function of series-FACTS (IPFC and SSSC) is to compensate for the voltage drop across the impedance transmission line while the shunt-FACTS (STATCOM) provide voltage support at the point of connection at the transmission line.

The efficiency of the proposed control laws are tested and analysed through computer simulation.

Keywords: Power system stabilization, FACTS, IPFC, SSSC, STATCOM, SMIB, VSC.

1. Introduction

There are several discrete supplementary controllers which can be initiated following a large disturbance. A comprehensive review of angle stability controls is presented in [1]. Braking resistors and switched series capacitors were among the earliest controllers used to enhance transient stability by changing the network parameters. In recent years, Flexible AC Transmission System (FACTS) controllers are considered to be viable solution to the problem of transient stability, due to their speed and flexibility. FACTS controllers based on voltage source converters use turn off devices like Gate Turn-Off Thyristors (GTO) [2]. The magnitude and angle of the fundamental frequency voltage injected by the converter is varied by controlling the switching instants of the GTO devices. These type of FACTS controllers have the advantages of reduced equipment

size and improved performance compared to variable impedance type controllers. In addition, converter-based FACTS controllers are capable of independently controlling both active and reactive power flow in the power system [2]. The FACTS devices that belong to this category are the static synchronous compensator (STATCOM), the static synchronous series compensator (SSSC) and Interline power flow controller (IPFC).

This paper studies the influence of the IPFC, the SSSC and the STATCOM on the synchronizing power and damping power. A single-machine infinite bus (SMIB) is used as a test system.

II. Structure and modeling (IPFC, SSSC and STATCOM)

II.1. STATCOM

As shown in the figure 1, the STATCOM used in this paper consists of three phase GTO based VSC and DC capacitor C . The STATCOM is connected to the transmission line through a step-down transformer.

The figure 2 shows a single phase equivalent circuit of the STATCOM where V_{sh} is the source voltage phasor. The transmission line is modeled by resistance r_{sh} and inductance L_{sh} . V_{sh} is the AC output voltage of STATCOM. r_{sh} and L_{sh} represent the shunt transformer resistance and leakage inductance respectively. The nonlinearities caused by the switching of the semiconductor devices, transformer saturation and controller time delays are neglected in the equivalent circuit and it is assumed that the transmission system is symmetrical [3, 4].

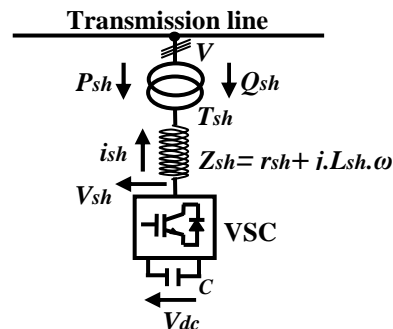


Fig. 1. Configuration of STATCOM

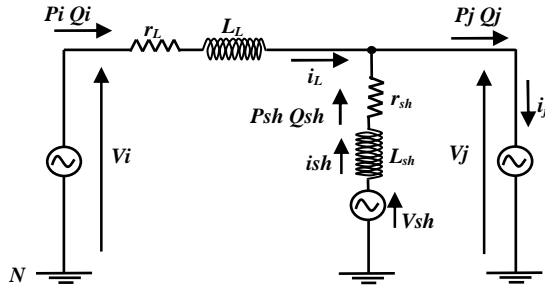


Fig. 2. Equivalent circuit of STATCOM system

The equations of the system in the model of Park transformation are:

$$\frac{d}{dt} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{r_{sh}}{L_{sh}} & \omega \\ \omega & -\frac{r_{sh}}{L_{sh}} \end{bmatrix} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \frac{1}{L_{sh}} \begin{bmatrix} V_{shd} \\ V_{shq} \end{bmatrix} - \begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} \quad (1)$$

The equations (2) and (3) below give the active and reactive powers:

$$P_{sh} = \frac{3}{2} (V_{shd} i_{shd} + V_{shq} i_{shq}) \quad (2)$$

$$Q_{sh} = \frac{3}{2} (V_{shd} i_{shq} - V_{shq} i_{shd}) \quad (3)$$

II.2. SSSC

The SSSC can be considered as a impedance compensation controller acting like a controlled series capacitor [5, 6, 7]. It consists a solid-state voltage source inverter, injecting an almost sinusoidal voltage, of variable magnitude, in series with a transmission line. It compensates the inductive voltage drop in the line by inserting capacitive voltage in order to reduce the effective inductive reactance of the transmission line. In contrast to series capacitor, the SSSC is able to maintain a constant compensating voltage in case of variable line current or controls the amplitude of the injected compensating voltage independent of amplitude of line current. A simply connected SSSC with transmission line is shown in figure 3.

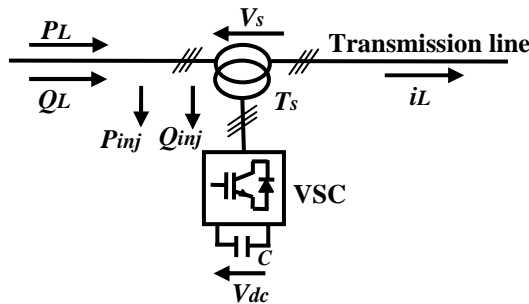


Fig. 3. Configuration of SSSC

The equivalent circuit of the SSSC is shown in figure 4.

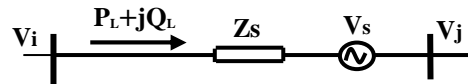


Fig. 4. Equivalent circuit of SSSC

The equivalent circuit of a multi-level SSSC system is shown in figure 4. The static inverter is represented by voltage sources V_s . The transmission line is modeled as a series combination of impedance $Z_s = r_s + jL_s\omega$.

By performing Park transformation, the current through the transmission line can be described by the following equations.

$$\frac{d}{dt} \begin{bmatrix} i_{ijd} \\ i_{ijq} \end{bmatrix} = \begin{bmatrix} \frac{r_s}{L_s} & \omega \\ -\omega & -\frac{r_s}{L_s} \end{bmatrix} \begin{bmatrix} i_{ijd} \\ i_{ijq} \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} - \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} - \begin{bmatrix} V_{jd} \\ V_{jq} \end{bmatrix} \quad (4)$$

$$\frac{dV_{dc}}{dt} = \frac{3}{2CV_{dc}} (V_{sd} i_{ijd} + V_{sq} i_{ijq}) \quad (5)$$

II.3. IPFC

In its general form the inter line power flow controller employs a number of dc-to-ac converters each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensators (SSSC) [3, 8]. The simplest IPFC consist of two back-to-back DC-to-AC converters (the one as master and the other as slave), which are connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common dc link as shown in figure 5. With this IPFC, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line [9, 10].

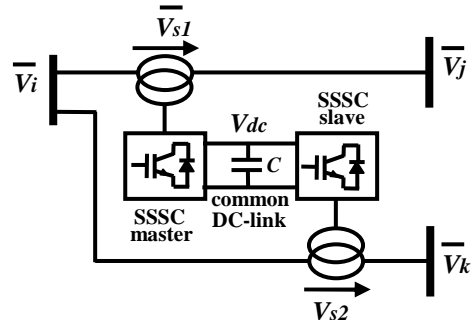


Fig. 5. Configuration of IPFC

The equivalent circuit of the IPFC is shown in figure 6.

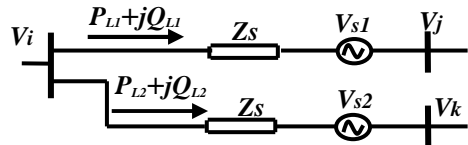


Fig. 6. Equivalent circuit of IPFC

The equivalent circuit of a multi-level IPFC system is shown in figure 6. The master and slaved inverters are represented by voltage sources V_{s1} and V_{s2} respectively. The transmission line is modelled as a series combination of impedance $Z_s=r_s+jL_s\omega$.

By performing Park transformation, the current through the transmission line can be described by the following equations.

$$\frac{d}{dt} \begin{bmatrix} i_{ijd} \\ i_{ijq} \end{bmatrix} = \begin{bmatrix} -\frac{r_s}{L_s} & \omega \\ \omega & -\frac{r_s}{L_s} \end{bmatrix} \begin{bmatrix} i_{ijd} \\ i_{ijq} \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} - \begin{bmatrix} V_{skd} \\ V_{skq} \end{bmatrix} - \begin{bmatrix} V_{jd} \\ V_{jq} \end{bmatrix} \quad (6)$$

$$\frac{dV_{dc}}{dt} = \frac{3}{2CV_{dc}} (V_{s1d}i_{ij1d} + V_{s1q}i_{ij1q} - V_{s2d}i_{ij2d} - V_{s2q}i_{ij2q}) \quad (7)$$

$$P_i = \frac{3}{2} (V_{id} \cdot i_{ijd} + V_{iq} \cdot i_{ijq}) \quad (8)$$

$$Q_i = \frac{3}{2} (V_{iq} \cdot i_{ijd} - V_{id} \cdot i_{ijq}) \quad (9)$$

Same for i_{ik}

III. Control strategy of STATCOM, SSSC and IPFC

In this case, the shunt converter voltage (for STATCOM) is decomposed into two components. One component is in-phase and the other in quadrature with the STATCOM bus voltage. Decoupled control system has been employed to achieve simultaneous control of the STATCOM bus voltage and the dc link capacitor voltage. The series converter of the IPFC and SSSC provides simultaneous control of real and reactive power flow in the transmission line [8, 9]. To do so, the series converter injected voltage is decomposed into two components. One component of the series injected voltage is in quadrature and the other in-phase with the IPFC bus voltage. The quadrature injected component controls the transmission line real power flow. This strategy is similar to that of a phase shifter. The in-phase component controls the transmission line reactive power flow. This strategy is similar to that of a tap changer [10, 11].

III.1. Current Regulation

The power flow control is then achieved by using properly designed controllers to force the line currents to follow their references. It is desired to obtain a fast response with minimal interaction between the real and reactive power together with a strong damping of the resonance frequency. With reference to equation (6), the interaction between the current loops is caused by the ωL coupling term. Decoupling is achieved by feeding back this term and subtracting [8, 9].

The figure 7 shows the diagram of this decoupling system.

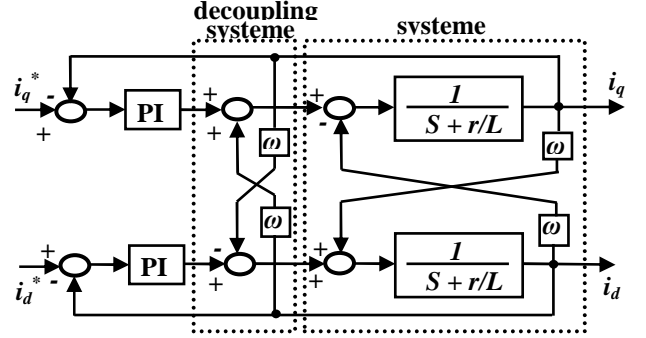


Fig. 7. PI decoupling system

$i=i_{sh}$, $r=r_{sh}$ and $L=L_{sh}$ four STATCM
 $i=i_{ij}$, $r=r_s$ and $L=L_s$ four IPFC and SSSC

The principle of this control strategy is to convert the measured three phase currents and voltages into d-q values and then to calculate the current references and measured voltages. Taking into account equations (8) and (9), we obtain below the equations (10) and (11). The superscript defines the reference quantities.

$$i_d^* = \frac{2}{3} \frac{(P^* V_d - Q^* V_q)}{V_d^2 + V_q^2} \quad (10)$$

$$i_q^* = \frac{2}{3} \frac{(P^* V_q + Q^* V_d)}{V_d^2 + V_q^2} \quad (11)$$

$V=V_{sh}$, $P=P_{sh}$, $Q=Q_{sh}$ four STATCOM
and $V=V_b$, $P=P_L$, $Q=Q_L$ four IPFC and SSSC

III.2. DC Voltage Regulation

The network equation is given by:

$$V_{dc}^2 = \frac{P_o^*}{CS} \quad (12)$$

The figure 8 shows the model control.

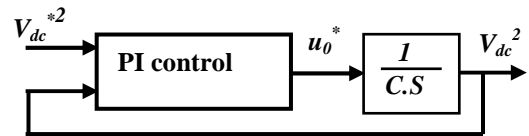


Fig. 8. PI Control for DC voltage

$u_o^*=P_{sh}^*$ four STATCOM, $u_o^*=i_{ikq}^*$ four IPFC and
 $u_o^*=i_{ijq}^*$ four SSSC.

The figure 9 shows the global diagram of control circuits of STATCOM.

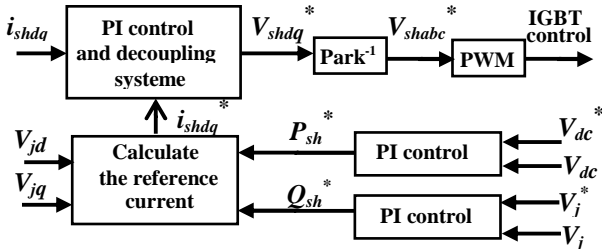


Fig. 9. The block diagram of control circuit of STATCOM

The diagram of control circuits of SSSC is given in the figure 10.

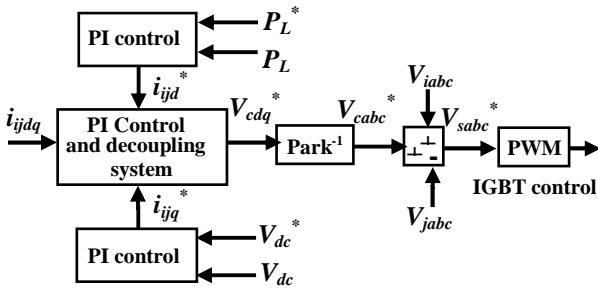
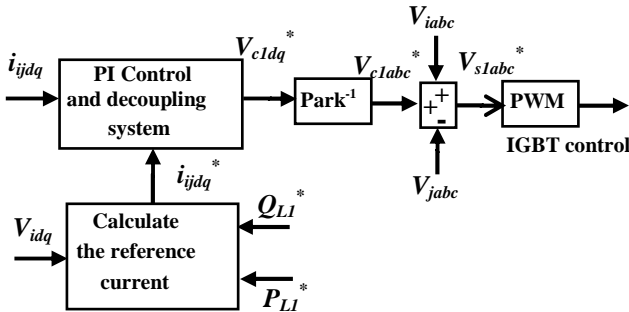
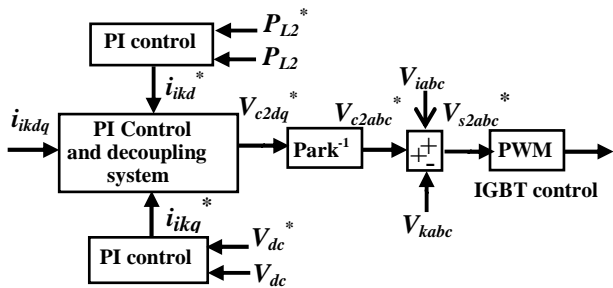


Fig. 10. The block diagram of control circuit of SSSC

The global diagram of control circuits of IPFC is given in the figure 11.



(a) Control circuit of IPFC master



(b) Control circuit of IPFC slave

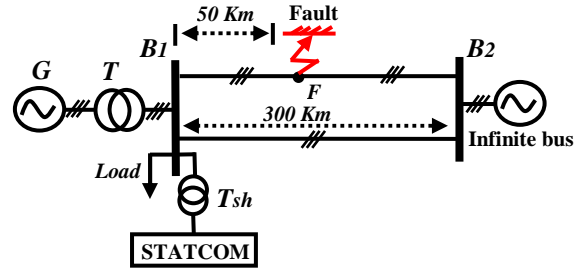
Fig. 11. The block diagram of control circuit of IPFC

IV. Simulation Results

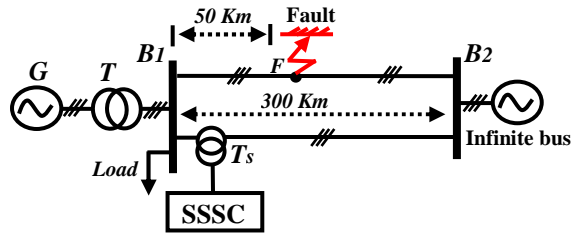
The network test of the figure 12 is a Single Machine Infinite Bus (SMIB) network made of a generator connected to an infinite power bus through a transformer and a 300km double transmission line. The data of the system is given in the Appendix. The FACTS (STATCOM- fig. 12. a, SSSC- fig.12. b and IPFC – fig. 12. c) is located close to bus 1 [10].

A three-phase fault is applied at locations F (50km away from the generator) individually as shown in figure 12. The sequence of events is specified as follows:

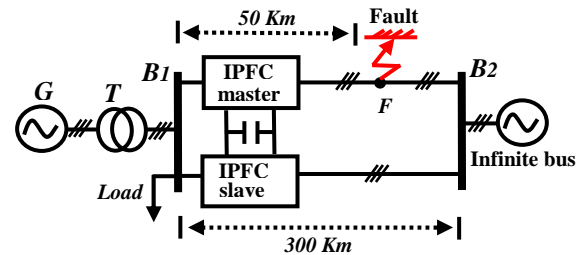
- Time $t=1$ sec, fault applied;
- Time $t=1.2$ sec, fault cleared;



(a) Application of STATCOM



(b) Application of SSSC



(c) Application of IPFC

Fig. 12. Disturbed SMIB power

IV.1. Simulation Results without classical regulation (CR)

Figures 13-17 show the behaviors of the characteristics of the generator (rotor speed, load angle, the speed according to the load angle, electrical power responses and voltage generator) without classical regulation for 200ms duration fault:

- the blue curve (with IPFC),
- the green curve (with SSSC),
- the brown (with STATCOM),
- the red curve (without any control).

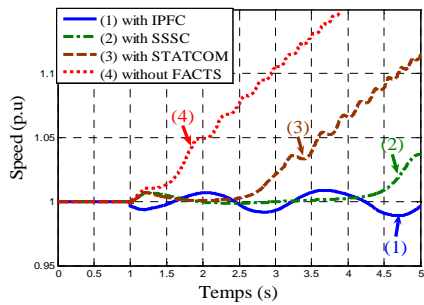


Fig. 13. Response of speed

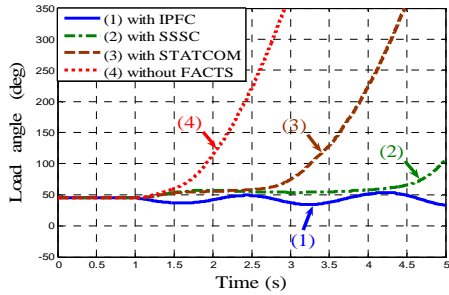


Fig. 14. Response of load angle

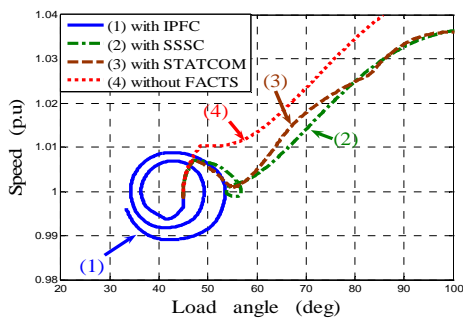


Fig. 15. The speed according to the load angle

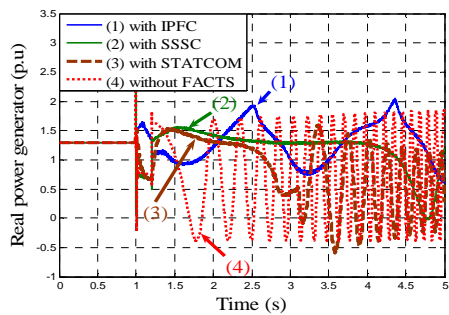


Fig. 16. Response of real power generator

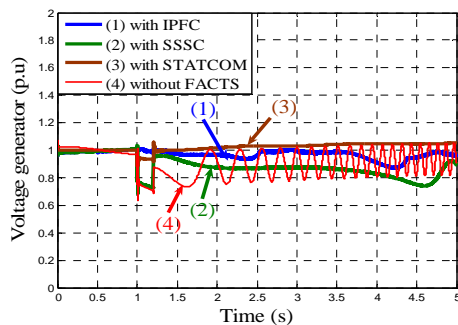


Fig. 17. Response of terminal voltage

After analyzing the results can be seen:

- a total system instability without FACTS application,
- a slight improvement (decrease of divergence) with STATCOM application,
- low stability of the system with IPFC or SSSC.

IV.2. Simulation Results with classical regulation

Figures 18-22 show the behaviors of the characteristics of the generator (rotor speed, rotor angle, the speed according to the load angle, electrical power responses and voltage generator) with classical regulation.

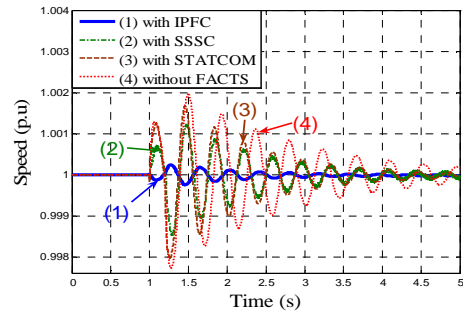


Fig. 18. Response of speed

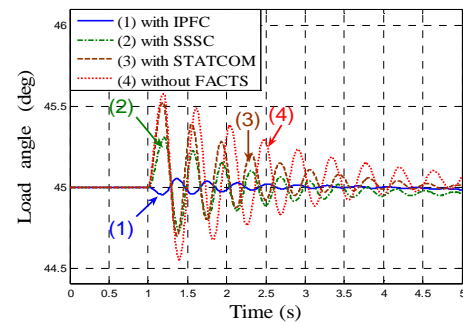
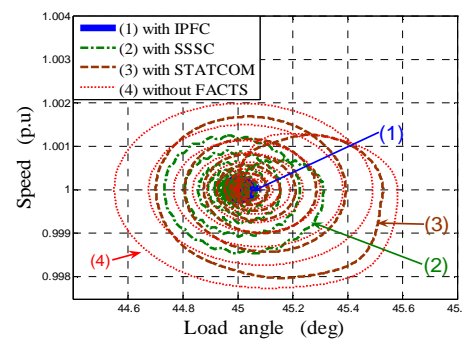
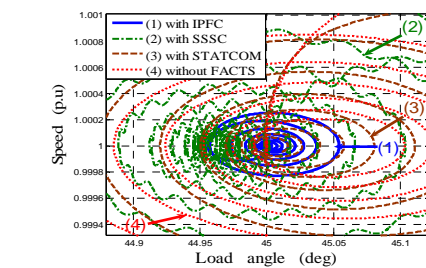


Fig. 19. Response of load angle



(a) The characteristic



(b) Zoom (figure a)

Fig. 20. The speed according to the load angle

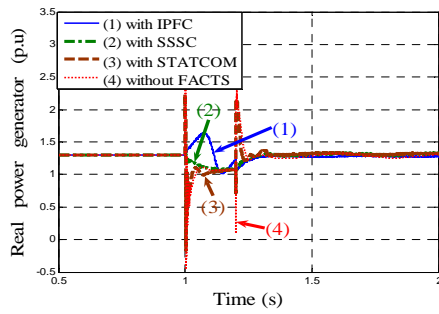


Fig. 21. Response of real power generator

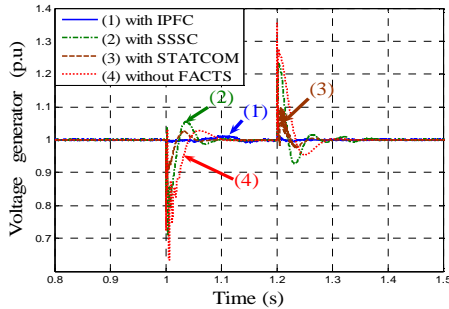


Fig. 22. Response of terminal voltage

The system is stable for all cases of control (IPFC, SSSC, STATCOM and without FACTS).

It can be readily seen that the IPFC performs better than SSSC and STATCOM, and the SSSC performs better than STATCOM.

On the other hand, IPFC, having both VSC1 (master) and VSC2 (slave), effectively damps out the oscillations caused by this severe disturbance in relatively short duration.

IV.3. Characteristics of FACTS (IPFC, SSSC and STATCOM) with classical regulation

The reference values of tie-line flows, PLine-1 and PLine-2 are respectively set to 0.24 pu and 0.24 pu at the real power flow controllers of IPFC while the DC link voltage is regulated at 1pu. The reactive power of IPFC master is fixed at 0 pu (Line-1). The same reference value of PLine-2 is set for SSSC real power flow controller. The AC voltage reference of STATCOM is regulated at 0.98 pu. The DC link voltage of STATCOM and SSSC is fixed at 1 pu.

Figures 23-25 show active and reactive power flows of transmission lines for 12-cycle fault (with IPFC).

- the blue curve (response),
- the green curve (reference).

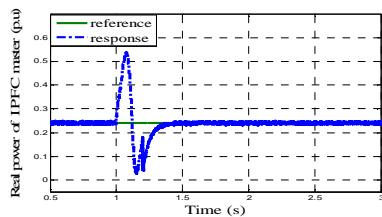


Fig. 23. Real power through transmission line and its reference of IPFC master

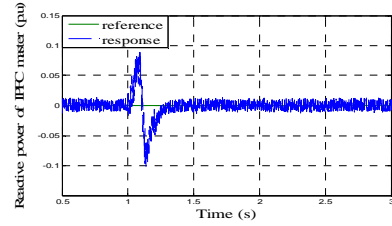


Fig. 24. Reactive power through transmission line and its reference of IPFC master.

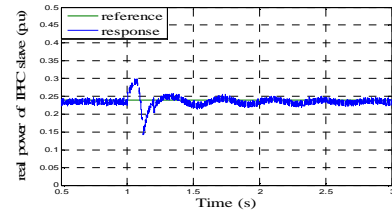


Fig. 25. Real power through transmission line and its reference of IPFC Slaved

Regulating the electrical energy is achieved by the impact of the IPFC on two transmission lines.

Figures 26-27 shows some selected time domain signals of the two VSCs of IPFC which reveal stable converter operation.

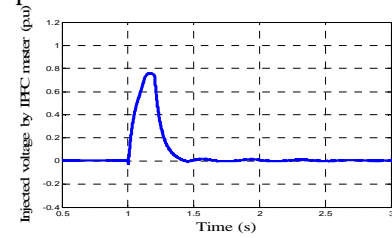


Fig. 26. Injected voltage by IPFC master

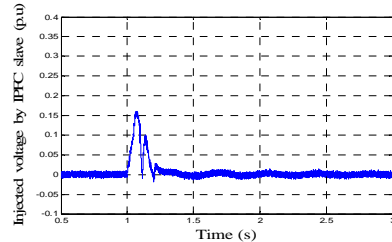


Fig. 27. Injected voltage by IPFC slave

Figures 28 shows active power flows of transmission lines for 12-cycle fault (with SSSC).

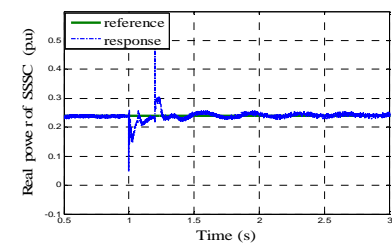


Fig. 28. Real power through transmission line of SSSC

Figure 29 shows the series voltage injected by SSSC

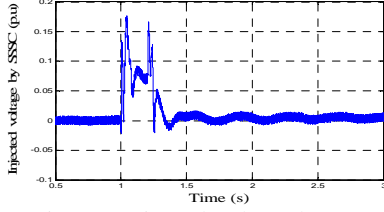


Fig. 29. Injected voltage by SSSC

Figures 30-31 show that the time responses of the DC link voltage of both SSSC and IPFC are practically the same which is highly required for proper VSC operation.

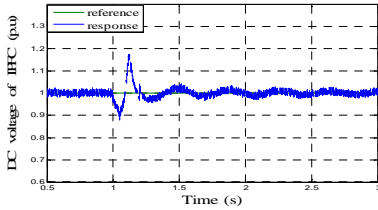


Fig. 30. dc-link voltage of the IPFC slaved.

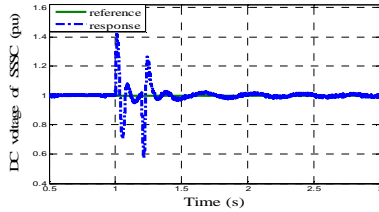


Fig. 31. DC-link voltage of the SSSC.

Figure 32 depicts that the dynamic voltage support within the study system is effectively provided by STATCOM at neighboring bus under the three-phase fault.

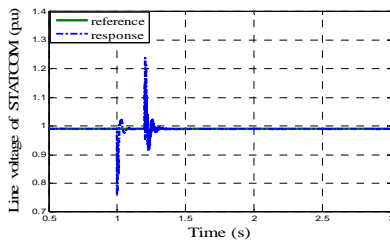


Fig. 32. Network voltage of the STATCOM

Figure 33 shows that the DC link voltage of the STATCOM decreases and increases for a short time when the fault occurs at point F and restored to its controlled value immediately, not affecting the operation of STATCOM.

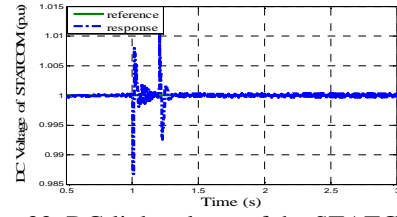


Fig. 33. DC-link voltage of the STATCOM

Figure 34 illustrates the shunt voltage injected by STATCOM

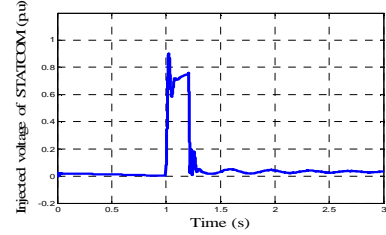


Figure. 34. The shunt voltage injected by STATCOM

Regulating the network voltage and the DC voltage is provided by the injection of active power and reactive power in the transmission line to the connection point of STATCOM.

V. Conclusion

This paper presented a systematic procedure for dynamic modeling of an simple power system fitted with FACTS controllers: series compensator and shunt compensator. The model can be used for digital computer simulation and/or design of globally coordinated controllers [11]. Simulation results indicated that both the SSSC, IPFC and STATCOM can significantly improve system damping. It is also observed that the IPFC can provide better damping than that of the (STATCOM, SSSC) and is in complete agreement with the theory described in the paper. However, use of the proposed technique to evaluate the additional damping provided by various FACTS devices for a more general fault case in a single-machine system requires further investigation [12]. Future work concerning this topic will be directed to extending the control strategy to transient stability control of a multi-machine power system with multiple FACTS devices.

Appendix

A. Power system data

$$S_b = 1000MVA, U_b = 500kV$$

Generator data:

$$S_{ng} = 2100MVA, H = 3.7s, V_{ng} = 13.8kV, f = 60Hz, \\ X_d = 1.305pu, X_d' = 0.296pu, X_d'' = 0.252pu, X_q = 0.474pu, \\ X_q' = 0.243pu, X_q'' = 0.18pu, T_d = 1.01s, T_d' = 0.053s, \\ T_{q0}'' = 0.1s.$$

Line data:

$f=60\text{Hz}$, $\text{Length}=300\text{km}$, $R_l=0.02546\Omega/\text{km}$,
 $R_0=0.3864\Omega/\text{km}$, $L_l=0.9337\times 10^{-3}\text{H}/\text{km}$, $L_0=4.1264\times 10^{-3}\text{H}/\text{km}$,
 $C_l=12.74\times 10^{-9}\text{F}/\text{km}$, $C_0=7.751\times 10^{-9}\text{F}/\text{km}$.

Transformer data:

$S_{nt}=2100\text{MVA}$, $V_{nt}=13.8/500\text{kV}$, 60Hz , $R_l=0.002$,
 $L_l=0$, $D1/Yg$ connection, $R_m=500$, $L_m=500$.

Load data:

Real power = 800MW
 Reactive power = 200Mvar

B. IPFC data

$r_s=1\Omega$, $L_s=0.001\text{H}$, $C_s=0.002\text{F}$.

Current regulation:

$K_p=50$, $K_i=300$.

DC voltage regulation:

$K_p=5$, $K_i=10$.

Active power regulation of IPFC slave:

$K_p=10$, $K_i=100$.

C. SSSC data

$r_s=1\Omega$, $L_s=0.001\text{H}$, $C_s=0.002\text{F}$.

Current regulation:

$K_p=50$, $K_i=300$.

DC voltage regulation:

$K_p=5$, $K_i=10$.

Active power regulation:

$K_p=10$, $K_i=100$.

D. STATCOM data

$R_{sh}=1\Omega$, $L_{sh}=0.001\text{H}$, $C_{sh}=0.002\text{F}$.

Current regulation:

$K_p=50$, $K_i=300$.

DC voltage regulation:

$K_p=5$, $K_i=10$.

Network voltage regulation of STATCOM:

$K_p=5$, $K_i=20$.

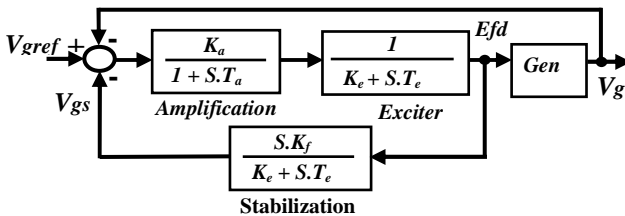
E. Classical regulation data

Voltage Regulation Data:

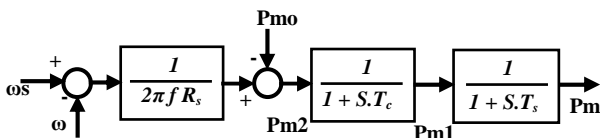
$K_a=100$, $T_a=0.01\text{sec}$, $K_e=1$, $T_e=0.01\text{sec}$, $K_f=0$, $T_f=0$.

Speed Regulation Data:

$R_s=0.001$, $P_{mo}=1.3\text{pu}$, $T_c=0.01\text{sec}$, $T_s=0.5\text{sec}$.



Bloc diagram for a representation of voltage regulation



Bloc diagram for a representation of speed regulation

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