International Journal of Natural and Engineering Sciences 7 (2): 52-58, 2013
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Power Oscillations Damping Through a Self-tuning Fuzzy Logic Damping Controller Integrated with a Static Synchronous Series Compensator

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Received: November 05, 2012
Accepted: December 21, 2012

Abstract

Power oscillations such as low frequency oscillations (LFO) are a common adverse experience in power systems which may result in instability problems and hence reduce the total and available transfer capability. It is well recognized that utilizing the flexible ac transmission systems (FACTS) technology yields different improvements in the power system such as better damping of electromechanical oscillations. This paper investigates the damping performance of the static synchronous series compensator (SSSC) equipped with a self-tuning fuzzy logic damping controller (STFLDC). At the outset, a modified Heffron-Phillips model of a single machine infinite bus (SMIB) system integrated with SSSC is established. In the following, well performance of the fuzzy logic damping controller (FLDC) rather than the conventional classic one is scrutinized. To be tolerant with the operating points changing, another fuzzy logic controller (FLC) which acts as the tuning controller is supplemented in the control loop. The tuning controller is designed such that in the case of severe disturbances, it will tune the output scaling factor to result in a better damping performance. Simulation studies validate the effective performance of the developed STFLDC in damping electromechanical oscillations which results in a robust and reliable one.

Keywords: Heffron-Phillips model, Low frequency oscillations (LFO), Self-tuning fuzzy logic damping controller, Single machine infinite bus (SMIB) power system, Static synchronous series compensator (SSSC).

INTRODUCTION

Todays, most of the power systems are operating near stability limits intended to supply increased electricity demand. On the other hand, interconnecting the large power systems have resulted in a more reliability and economical benefits. However, low frequency oscillations (LFO) with the frequencies in the range of 0.1 to 2 Hz are one of the direct results of the large interconnected power systems. These oscillations are frequent detrimental problems in large power systems since such oscillations often suffer from indigent damping [1]. These oscillations may come up to the overall rated capacity of a transmission line due to their superimposed effect on steady state flow a line. Hence, the oscillations would limit the total and available transfer capability by requiring higher safety margins. These electromechanical modes of oscillations are usually poorly damped which may increase the risk of instability of power system [1].

In the literature, different methods have been proposed to suppress the mentioned oscillations in the power system. Power system stabilizer (PSS) has been one of the traditionally devices used to damp out the oscillations [2]. During some operating conditions, PSS may not relieve the oscillations effectively and, hence, some other efficient alternatives are required besides the PSSs [3]. The introduction of flexible ac transmission system (FACTS) devices has initiated a new and more versatile approach to control the power system in a desired way [4]. FACTS controllers provide a set of interesting improvements including power flow control, reactive power compensation, voltage regulation, damping of oscillations, and so forth [5-12]. The static synchronous series compensator (SSSC) is a series FACTS device performing based on a solid-state voltage source converter (VSC) to produce a controllable ac voltage in quadrature with the line current [13]. By this way, the SSSC imitates as an inductive or capacitive reactance and hence controls the flow of the power in the transmission lines.

In [14], author has developed the damping function for the SSSC. By properly designing a supplementary power oscillations damping (POD) controller, the SSSC would be capable of damping the fluctuations as an ancillary duty [14]. In the literature, different methods have been proposed to design a POD controller for SSSC. For example, in [14] authors have used the phase compensation method to develop a supplementary damping controller for SSSC. The chief problem associated with the mentioned methods relates to its control process which depends on the linearized model. The other frequently used approach is the proportional-integral (PI) controller. Although the PI controllers offer simplicity with an easy design, their functionality depreciates when wide variations occur in system conditions or large disturbances happen [15].

In this area, new effective solutions are proposed. In recent years, fuzzy logic controllers (FLCs) are coming as an impressive tool to circumvent these drawbacks. The FLC integrates qualitative and quantitative information regarding the system operation by some hierarchy. To be more precise, fuzzy logic yields a comprehensive concept to describe and measurement of the systems. The fuzzy logic systems interpret human understanding to a program in order to arrive at decisions or to better control of the system [16,17]. Fuzzy logic includes fuzzy sets to represent non-statistical uncertainty in processes [18]. There are some manuscripts which have demonstrated the successful application of FLC for transient stability enhancement of a power system. In [19], Limyingcharone et al. have used a fuzzy supplementary controller with the aim of achieving low frequency oscillations damping.

The main contribution of this research is to design a supplementary self-tuning FLDC (STFLDC) to attenuate the power oscillations by SSSC. The investigation is carried out for a power system including a single machine with an infinite bus (SMIB) integrated with a SSSC. In the sequel, the linearized Heffron-Phillips model [20] of the examined plant is evolved. An auxiliary FLC is utilized to modulate the amplitude modulation index during the transients to extend the stability capability of the system. Subsequently, aiming to provide a fruitful investigation, a comparative study is developed where the FLC is compared with a conventional classic controller. To provide a robust and reliable controller, another FLC is designed as the tuning controller. It is shown that the performance of STFLDC is more efficient than all and hence would be a good option for system designs and covers more range of operating points. Simulation results using MATLAB/Simulink exhibits the superior damping of STFLDC.

Power System Modeling

This section is dedicated to extract an exact linearized Heffron-Phillips model for the investigated power system. As depicted in Figure 1, the SMIB integrated with SSSC is selected as the testbed. Here, X_T is the transformer reactance and XL corresponds to transmission line reactance. Also, V_t and V_b represent the voltages for generator terminal and infinite bus. A simple SSSC consisting of a three-phase VSC is incorporated in the transmission line. The SSSC performance is organized on the well-known pulse width modulation technique. For the SSSC, X_{SCT} is the transformer leakage reactance; V_{INV} is the series injected voltage; C_{DC} is the DC link capacitor; V_{DC} is the voltage at DC link; m represents amplitude modulation index and ψ is the phase angle of the series injected voltage.

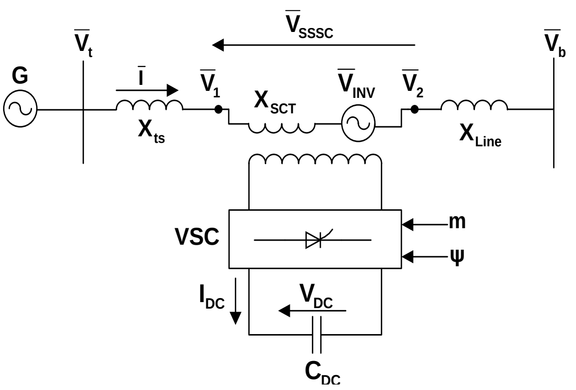


Figure 1. A single machine infinite bus power system with a SSSC

Nonlinear Dynamic Model Of The Power System With SSSC

As the first step, a nonlinear model for the examined system is extracted where the resistance of the total ingredients of the testbed have been neglected. The equations specifying the dynamic performance of the SSSC can be written as follows [14].

$$\bar{I}_1 = I_d + jI_q = I\angle\varphi$$
$$\bar{V}_{INV} = mkV_{DC}(\cos\psi + j\sin\psi) = mkV_{DC}\angle\psi$$
$$\psi = \phi \pm 90$$
$$\frac{dV_{DC}}{dt} = \frac{mk}{C_{DC}}(I_d\cos\psi + I_q\sin\psi) \qquad (1)$$

Where k is the fixed ratio between the converter AC and DC voltages that depends on the structure of the inverter. For a simple three-phase VSC, k is equal with $3/4$ [4]. Most of the times, SSSC performs as a pure capacitor or inductor; hence, the only main controllable parameter for SSSC is the amplitude modulation index$m$.

For the work at hand, the IEEE Type-ST1A excitation system is considered. Figure 2 displays the block diagram of the excitation system where the terminal voltage V_t and the reference voltage V_{ref} are the input signals. K_A is the gain and T_A is the time constant for the excitation system. The dynamic model of the power system in Figure 1 would be as follows [21].

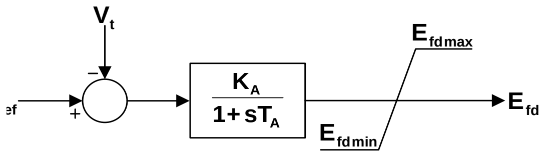


Figure 2. IEEE Type-ST1A excitation system

$$\dot{\delta} = \omega_0(\omega - 1) \qquad (2)$$

$$\dot{\omega} = \frac{P_m - P_e - P_D}{M} \qquad (3)$$

$$\dot{E}'q = \frac{(-E_q + E_{fd})}{T'_{do}} \qquad (4)$$

$$\dot{E}_{fd} = \frac{-E_{fd} + K_A(V_{ref} - V_t)}{T_A} \qquad (5)$$

$$\dot{V}_{DC} = \frac{3m}{4C_{DC}}(I_d\cos\psi + I_q\sin\psi) \qquad (6)$$

where

δ : Rotor angle of synchronous machine in radians

ω : Rotor speed in rad/sec

P_m : Mechanical power input to the generator

P_e : Electrical power of the generator

$P_D = D(\omega - 1)$, D: Damping coefficient

E'_q : Generator internal voltage

E_{fd} : Generator field voltage

I_d : d-axis current

I_q : q-axis current

Linear Dynamic Model Of The Power System With SSSC

The linear Heffron-Philips model for the SMIB system integrated with SSSC is extracted by linearizing the nonlinear model for a nominal operating point [14].

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \qquad (7)$$

$$\Delta\dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \qquad (8)$$

$$\Delta\dot{E}'_q = \frac{(-\Delta E_q + \Delta E_{fd})}{T'_{do}} \qquad (9)$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_A(\Delta V_{ref} - \Delta V_t)}{T_A} \qquad (10)$$

$$\Delta\dot{V}_{DC} = K_7\Delta\delta + K_8\Delta E'q + K_9\Delta V_{DC} + K_{DCm}\Delta m$$
(11)

Where

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'q + K_{pDC}\Delta V_{DC} + K_{pm}\Delta m$$
(12)

$$\Delta E_q = K_4\Delta\delta + K_3\Delta E'q + K_{qDC}\Delta V_{DC} + K_{qm}\Delta m$$
(13)

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'q + K_{vDC}\Delta V_{DC} + K_{vm}\Delta m$$
(14)

Figure 3 exhibits the transfer function representation for the modified Heffron-Phillips model of the SMIB system with SSSC.

State Space Representation of Linear Model

The state-space representation for the modified Heffron-Phillips model:

$$\dot{X} = AX + BU \qquad (15)$$

Where X and U are defined as the state vector and control vector respectively.

$$X = [\Delta\delta \quad \Delta\omega \quad \Delta E'q \quad \Delta E_{fd} \quad \Delta V_{DC}]^T \qquad (16)$$

$$U = [\Delta m] \qquad (17)$$

With respect to (7)-(15), the corresponding system matrix namely A, and the control matrix namely B, are obtained for the investigated power system.

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-k_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K7 & 0 & K8 & 0 & K9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ -K_{pm} \\ -K_{qm} \\ -K_{vm} \\ K_{DCm} \end{bmatrix}$$

The nominal operating point for the power system is set to the given values.

$$P_e = 0.8\,pu,\ Q_e = 0.144\,pu,\ V_b = 1\,pu$$

The Heffron-Phillips model constants are calculated based on the given values for the nominal operating point and some other data which are reported in the Appendix A. Also the parameters of SSSC are given in the Appendix B. Eventually; Appendix C gathers all of the constants computed for the system model depicted in Figure 3.

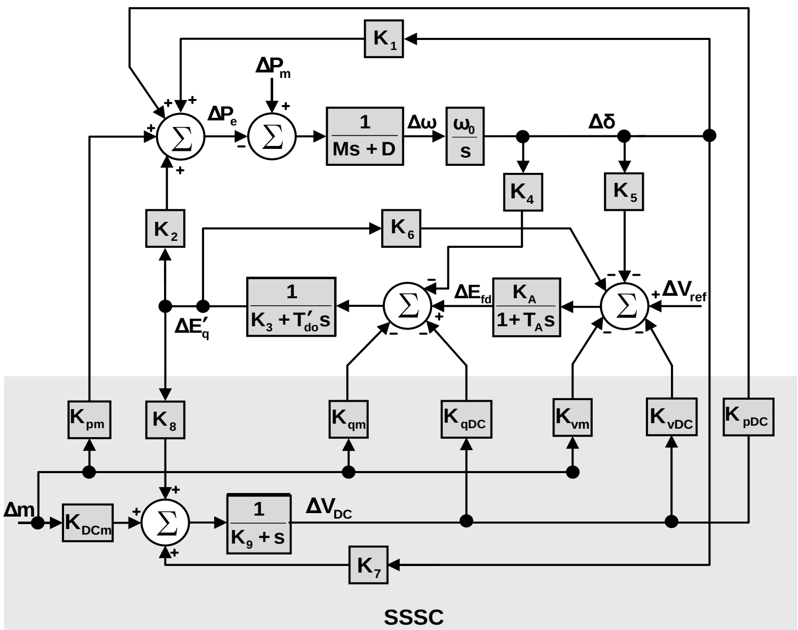


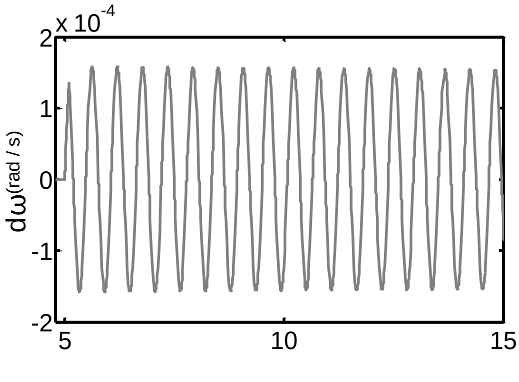
Figure 3. Heffron-Phillips model of SMIB system integrated with SSSC

Design of Damping Controller and Performance Analysis

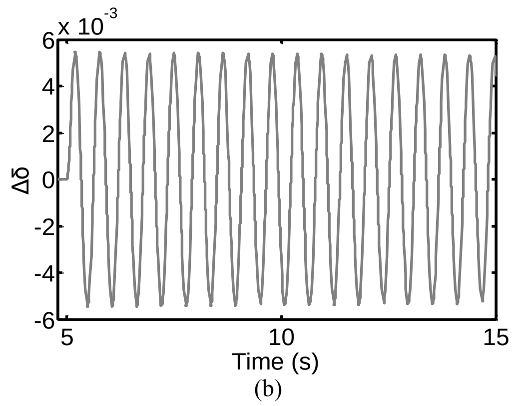
Aiming to damp the low frequency oscillations, two sorts of damping controllers are designed and compared with each other. In the investigated system, as mentioned earlier, the SSSC series converter amplitude modulation index namely m, provides a control signal to yield better damping of oscillations. In the subsequent sections, each controller is individually discussed in detail.

Classic Damping Controller (CDC)

A step change is considered as the contingency in mechanical power ($\Delta P_m = 0.01$) which occurs at t=5sec and lasts for 0.1 sec. At the beginning, the SSSC has no damping controller. The angular velocity deviation and also the load angle deviation responses are displayed in Figure 4 (a) and (b) respectively. This figure reveals that when the system has no damping controller, there is a very poor damping in LFO; hence an auxiliary damping controller is essentially required to improve the transient stability of the system.



(a)



(b)

Figure 4 (a) and (b).LFO damping performance with no damping controller

In this subsection a classic damping controller (CDC) is designed and added to the main control loop of the SSSC. Figure 5 displays the CDC structure. It is composed of a gain block, a washout filter and a lead-lag compensator. $\Delta\omega$ denotes the angular velocity deviation which is adopted as the feedback input signal where as other measurable signals, such as frequency, line real power, etc have been selected by the other literatures [11].

The gain setting of the damping controller is adjusted so as to attain the desired damping ratio of the oscillations. Washout circuit is utilized to block the auxiliary controller not to respond to the steady-state power conditions. The parameters of the lead-lag compensator are such tuned that the phase shift between the speed deviation and the resulting electrical torque is compensated. By this way, an additional electrical damping torque in phase with the speed deviation is achieved. In the testbed, simulation studies are used to settle the initial parameter settings for the controller by a trial-error method. The detailed data for classic damping controller is presented in Appendix A. Figure 6 demonstrates that by considering the classic damping controller, the oscillations are more effectively damped. The operation of this controller mainly depends on the operating point. For the changing operating conditions, this classic controller will not be as effective as for its initial operating point.

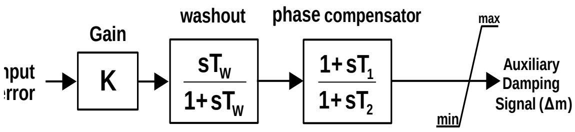


Figure 5. Auxiliary classic damping controller

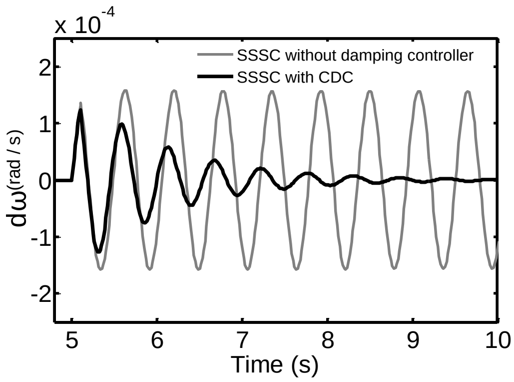


Figure 6. CDC performance in Low frequency oscillations damping

Auxiliary Fuzzy Logic Damping Controller (FLDC)

As explained in the preceding sections, although the classic controllers offer simplicity with an easy design, their performance depreciates when vide variations occur in the system conditions or large disturbances happen. Consequently, to ensure the effective performance of damping controller over wide range of system operations and also to increase the transient stability of the system, a supplementary fuzzy logic controller (FLC) based on the Mamdani's fuzzy inference method is designed for the SSSC input. FLC generates the required small change for amplitude modulation index to control the magnitude of the injected voltage. The centroid defuzzyfication technique was used in this fuzzy controller.

Figure 7 demonstrates the FLC structure. In this case, a two–input, one–output FLC is considered. The input signals are angular velocity deviation ($\Delta\omega$) and load angle deviation ($\Delta\delta$) and the resultant output signal is the amplitude modulation index (Δm) for SSSC converter.

K_1 and K_2 are the input scaling factors to scale the input signals in the range of [-1,1]; and Ko is the output scaling factor to scale the output to the real values. The presented FLC has a very simple structure. The membership functions of the input and output signals are shown in Figure 8 (a), (b) and (c) respectively. There are two linguistic variable for each input variable, including, "Positive" (P), and "Negative" (N). On the other hand, for the output variable there are three linguistic variables, namely, "Positive" (P), "Zero" (Z), and "Negative" (N). The rules used for the FLC are chosen as follows:

1If $\Delta\omega$ is P and $\Delta\delta$ is P, then Δm is P.
2If $\Delta\omega$ is P and $\Delta\delta$ is N, then Δm is Z.
3If $\Delta\omega$ is N and $\Delta\delta$ is P, then Δm is Z.
4If $\Delta\omega$ is N and $\Delta\delta$ is N, then Δm is N.

Figure 9 demonstrates the performance of the FLDC in damping of oscillations. As it is seen, the FLDC performs better than the CDC in low frequency oscillations damping. Simulation results validate the efficiency of the proposed FLDC and its better performance is emphasized.

The FLDC demonstrates a good performance when the operating conditions are similar to the conditions considered for designing the controller. In the other operating conditions, the designed controller would not be capable of settling down the oscillations. Therefore, this controller should be capable of tuning itself during its operation. In this regard, another FLC is suitably added to the FLDC which tunes the output gain by the coefficient α. Figure 10 shows the structure of this controller. To design the tuning controller, some severe cases are considered. By simulation studying of these cases, it is distinguished that in the worst cases, if α is equal with the end threshold of 1.5, the total controller will demonstrate a satisfactory response. Hence, α is set to vary in the following range, namely $1 \leq \alpha \leq 1.5$. The membership functions for the inputs are the same as before except a Zero (Z) membership function added. For the output, the membership functions are depicted in Figure 11. These membership functions are marked with the respective linguistic labels, S (Small), M (Medium), and B (Big). The rules with two proposed inputs, $\Delta\omega$ and $\Delta\delta$, are listed in the Table 1. Also Figure 12 shows the control surface for the tuning controller.

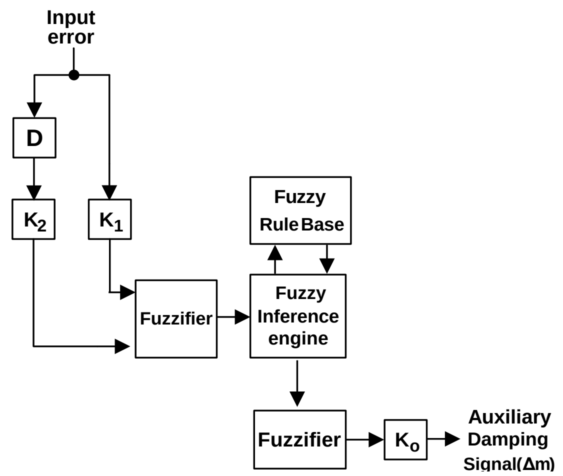


Figure 7. Fuzzy logic damping controller structure

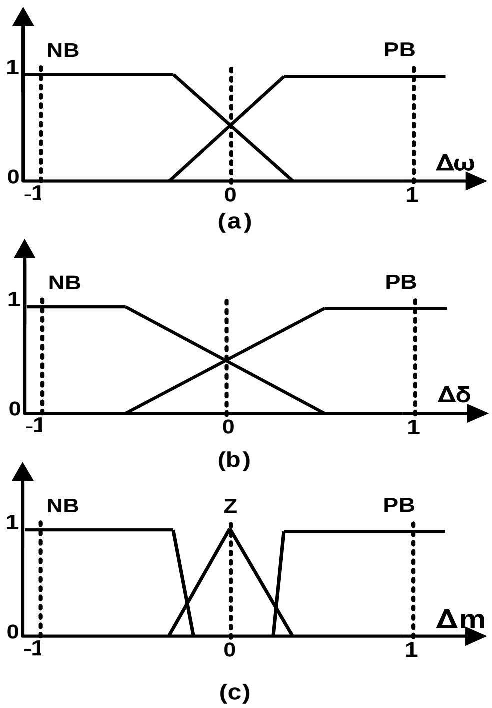


Figure 8 (a), (b). inputs membership function, (c).output membership function

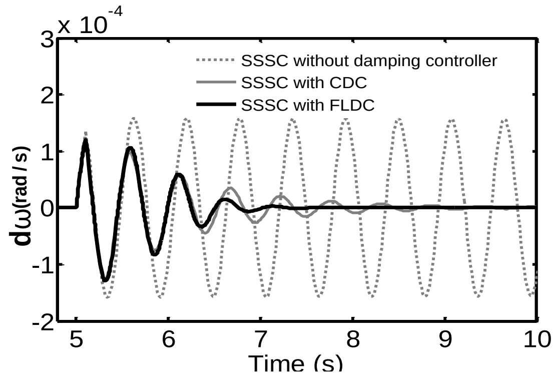


Figure 9. Comparison of CDC and FLDC in Low frequency oscillations damping

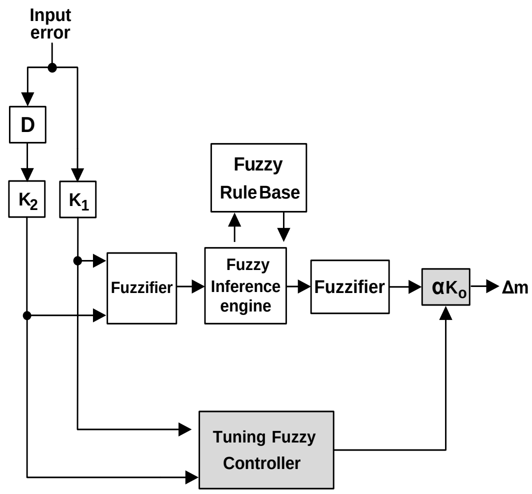


Figure 10. STFLDC structure

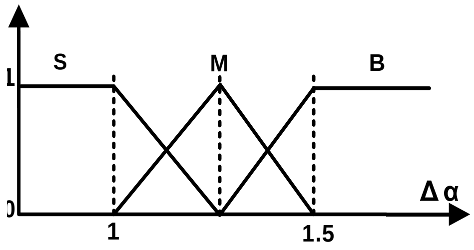


Figure 11. Membership functions of tuning controller; α

Table 1. Fuzzy rules of tuning FLC

$\Delta\delta$ / $\Delta\omega$	**N**	**Z**	**P**
N	B	M	S
Z	M	S	M
P	S	M	B

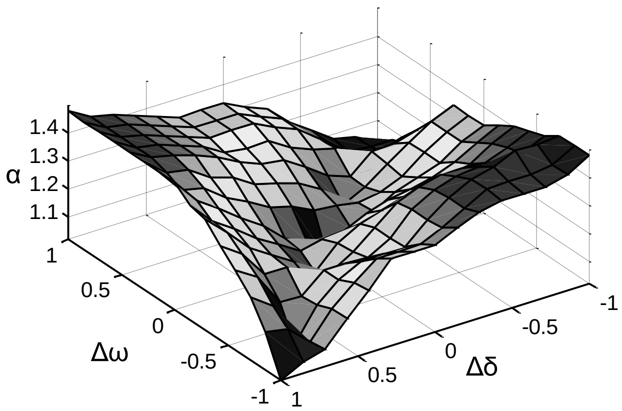


Figure 12. The rule surface for tuning controller

Performance of STFLDC in low frequency oscillations is shown in Figure 13 where the best damping performance is deduced for this controller among the previously examined. STFLDC provides more reliability and covers a wide range of operating points. Also Figure 14 demonstrates the desired pole shifting achieved with STFLDC in comparison of the power system without damping controller.

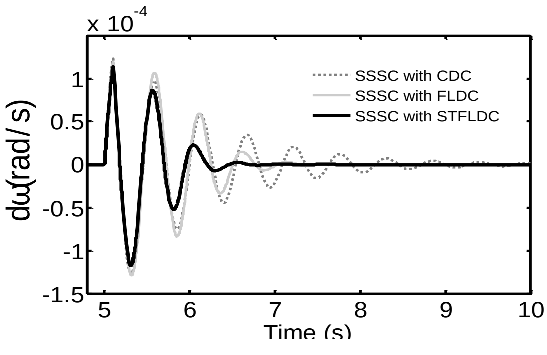


Figure 13. Performance of STFLDC in low frequency oscillations damping

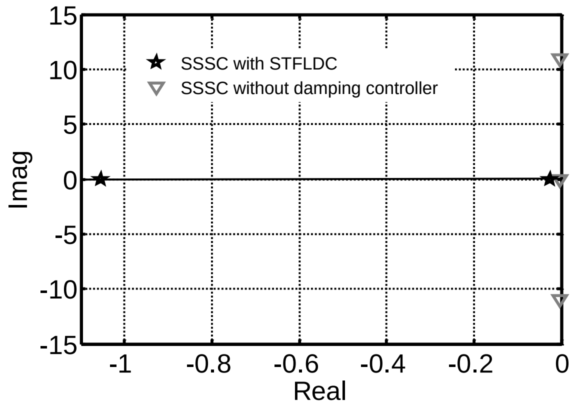


Figure 14. Performance of STFLDC in system pole shifting

CONCLUSION

This manuscript serves an exact investigation to obtain a complete linearized Heffron-Phillips model SMIB power system equipped with an SSSC to study LFO damping with an auxiliary FLC. It was shown that a contingency in power system will cause to initiate power oscillations. In the sequel, two types of controllers, namely, the CDC and the FLC were designed to damp the system oscillations. A comparative study between the FLDC and CDC shows that the proposed FLDC has superior performance and influence in transient stability enhancement and oscillations damping. Aiming to achieve a robust damping controller which covers wide operating points, a tuning FLC is added to the control loop of the FLDC and constructs the STFLDC. The tuning controller tunes the output of the FLDC and makes it a self tuning controller in response to changes of operating point. Simulation results validate the efficiency of the proposed STFLDC and its better performance in damping the low frequency oscillations among the studied controllers is emphasized.

Appendix A
Power System Parameter
Generator:
M=2H=6 MJ/MVA, D=0
T'_{do}=5.044 s
X_d=0.1 pu, X_q=0.06 pu, X'_d=0.025 pu
f_0=60 Hz, $\omega_0=2\pi f0$
Excitation System:
K_A=5, T_A=0.005 s
Transmission Line and Transformer Reactances:
X_{Line}=0.2 pu, X_{ts}=0.2 pu

Appendix B
SSSC Parameters
C_{DC}=1 pu; V_{DC}=0.5 pu; m=0.15; X_{SCT}=0.1 pu

Appendix C
Heffron-Phillips Model Constants
K_1=1.9014; K_2=0.6735; K_3=1. 1429
K_4=0.0498; K_5=-0.0127; K_6=0. 9517
K_7=-0.1759; K_8=0.0302; K_9= 1.402×10-4
K_{DCm}=-0.4255; K_{pDC}=0.0244; K_{qDC}=0.0106; K_{vDC}= -0.0035
K_{pm}=0.0839; K_{qm}=0.0354; K_{vm}=-0.008

REFRENCES

[1] Kundur P.1994.Power System Stability and Control.NY, USA: McGraw- Hill;

[2] Larsen EV, Swann DA.1981.Applying power system stabilizers, P-III, practical considerations. IEEE Trans Power App Syst; Vol 100: 3034–3046.

[3] Lei X, Lerch EN,Povh D. 2001. Optimization and coordination of damping controls for improving system dynamic performance. IEEE Trans Power Syst; Vol 16: 473–480.

[4] Hingorani NG, Gyugyi L.2000. Understanding FACTS: Concepts and technology of flexible ac transmission system. NY, USA: IEEE Press.

[5] Douglas JG, Heydt GT.1998. Power flow control and power flow studies for systems with FACTS devices. IEEE Trans on Power Syst; Vol 13: 60-65.

[6] Taheri H, Shahabi S, Taheri Sh, Gholami A.2009. Application of static synchronous series compensator (SSSC) on enhancement of voltage stability and power oscillation damping. IEEE Conf.:533 – 539.

[7] Larsen EV, Sanchez-Gasca JJ, Chow JH.1995. Concepts for design of FACTS controllers to damp power swings.IEEE Trans on Power Syst; Vol 10: 948-956.

[8] El-Moursi MS, Bak-Jensen B, Abdel-Rahman MH.2010. Novel STATCOM controller for mitigating SSR and damping power system oscillations in a series compensated wind park. IEEE Trans. Power Del;Vol 25: 429–441.

[9] Varma RK, Auddy S, and Semsedini Y. 2008. Mitigation of subsynchronous resonance in a series-compensated wind farm using FACTS controllers," IEEE Trans Power Del;Vol 23: 1645–1654.

[10] Mathur RM, Varma RK.2002. Thyristor-Based FACTS Controllers for Electrical Transmission Systems.NY, USA: IEEE Press and Wiley Interscience;

[11] Majumder R, Pal BC, Dufour C, Korba P. 2006. Design and real-time implementation of robust FACTS controller for damping inter-area oscillation. IEEE Trans Power Syst; Vol21: 809–816.

[12] Prasai A, Divan DM.2008.Zero-energy sag correctors optimizing dynamic voltage restorers for industrial applications. IEEE Trans Ind Appl;Vol 44: 1777–1784.

[13] Gyugyi L, Schauder CD, Sen KK.1997.Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines. IEEE Trans Power Del; Vol 12: 406–417.

[14] Wang HF.1999.Design of SSSC damping controller to improve power system oscillation stability. AFRICON, IEEE: 495 – 500.

[15] Dash PK, Mishra S, Panda G.2000. Damping multimodal power system oscillations using a hybrid fuzzy controller for series connected FACTS devices. IEEE Trans Power Syst; Vol. 15: 1360–1366.

[16] Cornelius TL.1999. Fuzzy Theory Systems: Techniques and Applications. San Diego, California, USA: Academic Press.

[17] Sugeno M, Nguyen HT, Prasad NR.1999. Fuzzy Modeling and Control: Selected Works of M. Sugeno. Boca Raton:CRC Press.

[18] Ying H.1999. Fuzzy Control and Modeling: Analytical Foundations and Applications. In: Akay M, editor.NY, USA: IEEE Press Series on Biomedical Engineering.

[19] Limyingcharone S, Annakkage UD, Pahalawaththa NC.1998.Fuzzy logic based unified power flow controllers for transient stability improvement. IEE Conference Proc; pp. 225–232.

[20] Heffron WG, Phillips RA.1952. Effect of a modern amplidyne voltage regulator on under excited operation of large turbine generator.AIEE T. Vol71.

[21] Wang HF, Swift FJ.1997. A unified model for the analysis of FACTS devices in damping power system oscillations. Part I. single-machine infinite-bus power systems. IEEE Trans Power Del. Vol 12: 941–946.