Power Oscillations Damping by Static Var Compensator Using an Adaptive Neuro-Fuzzy Controller

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***Abstract*:** In large interconnected power systems, Low frequency oscillations (LFO) are a well-known adverse phenomenon which may increase the risk of instability for the power system. This manuscript investigates the damping performance of the Static Var Compensator (SVC) equipped with an auxiliary controller based on Adaptive Neuro-Fuzzy Inference System (ANFIS). First of all, a modified Heffron-Phillips model of the single machine infinite bus (SMIB) system installed with SVC is established. In the following an auxiliary fuzzy logic controller (FLC) for SVC is designed to enhance the transient stability of the power system. Next, an ANFIS based auxiliary damping controller is well-designed and compared with the FLC. In order to evaluate the performance of the proposed ANFIS based controller in damping of LFO, the SMIB power system is subjected to a disturbance such as changes in mechanical power. The complete digital simulations are performed in the MATLAB/Simulink environment to provide comprehensive understanding of the issue. Simulation results demonstrate that the developed ANFIS based controller would be more effective in damping electromechanical oscillations in comparison with the FLC and conventional proportional-integral (PI) controller.

Keywords: Low Frequency Oscillations (LFO), Static Var Compensator (SVC), Single Machine Infinite Bus (SMIB) power system, Heffron-Phillips model, ANFIS based damping controller.

I. INTRODUCTION

Interconnecting the large power systems together, has resulted in a more reliability and economical viability in the utility sections. However, low frequency oscillations (LFO) with the frequencies in the range of 0.2 to 2 Hz are one of the direct results of the large interconnected power systems. The power oscillations may approach to entire rating of a transmission line, as they are superimposed on steady state power flow in the line. Consequently, these oscillations would limit the total and available transfer capability by demanding higher safety margins. These electromechanical modes of oscillations are usually weakly damped which may result in a higher risk of instability of power system. Therefore, to maintain the stability of the entire system, it is vital to damp the electromechanical oscillations in a very short time [1]-[2].

Different methods have been suggested to mitigate the oscillations in the power system. Power system stabilizer (PSS) has been one of the traditionally devices used to damp out the oscillations [3]. It is reported that during some operating conditions, PSS may not damp the oscillations effectively; hence, other effective substitutes are required in addition to PSSs [4].

Recently, emerging of the flexible ac transmission system (FACTS) devices has directed the way to a new and more versatile approach to control the power system in a desired manner [5]. FACTS controllers offer a series of remarkable capabilities such as reactive power compensation, voltage regulation, power flow control, damping of oscillations, and etc [6]-[11]. The static var compensator (SVC) is one of the shunt connected FACTS devices. Usually the SVC is a delta-connected Thyristor Controlled Reactor - Fixed Capacitor (TCR-FC) which connects in parallel with the load. The primary task of the SVC is to control its bus voltage across a protected load. The equivalent susceptance of the SVC is adjusted in each phase by controlling the conducting angles of the TCRs [5], [12]. By this way it is possible to adjust the SVC susceptance in the value that is needed for reactive power compensation and hence voltage regulation.

Along with its main duty, SVC is capable of realizing some other ancillary duties such as power oscillation damping (POD). In the literature, different methods have been proposed to design a POD controller for SVC. Phase compensation method is one of the earliest methods utilized to develop a supplementary damping controller for SVC. The main problem associated with this method is that the control process is based on the linearized power system model. Proportional-integral (PI) controller is the other frequently used approach. Although the PI controllers present simplicity and ease of design, their operation gets worth when the system conditions vary widely or large disturbances occur [13]. In this field, some new stabilizing control solutions for power system have been presented. Recently, Fuzzy Logic Controllers (FLCs) and Artificial Neural Network Controllers (ANNCs) have appeared as an efficient tool to circumvent these drawbacks [14]-[15].

The FLC integrates qualitative and quantitative knowledge about the system operation through some hierarchy. To be more precise, fuzzy logic provides a general concept for description and measurement of systems [16] - [17]. More recently, the use of ANFIS based power oscillation damping controllers has been introduced as an effective way. The ANFIS combines the advantages of FLCs and ANNCs together. The learning ability of ANNC is used to adjust the parameters of FLC in different conditions to achieve a better performance [18]-[20].

This paper investigates the design of a supplementary ANFIS based controller to attenuate power oscillations by SVC. The investigation is performed for a single machine infinite bus (SMIB) power system installed with an SVC. In the following, the linearized Heffron-Phillips model [21] of the investigated plant is developed. An auxiliary ANFIS based controller is utilized to modulate the equivalent susceptance of the SVC during the transients to enhance the stability of the power system. The initial setting of membership functions for the FLC is done based on the dynamical behavior of SVC. Then membership functions are optimized by the use of ANNC. Subsequently, aiming to provide a fruitful investigation, a comparative study is developed where the ANFIS based controller is compared with conventional FLC and PI controller. Simulation results using MATLAB/Simulink validates the superior damping of LFO obtained with ANFIS based controller.

II. SINGLE MACHINE INFINITE BUS POWER SYSTEM

This section is devoted to establish a linearized Heffron-Phillips model for the power system. As illustrated in Fig. 1, a single machine infinite bus (SMIB) system equipped with an SVC is considered as the sample power system. In this figure, R_L and X_L correspond to the resistance and reactance of the transmission line respectively. Also, V_t and V_b represent the generator terminal voltage and infinite bus voltage respectively. A simple SVC consisting of a three-phase TCR-FC is incorporated in the generating terminal. The initial task for the SVC is to regulate its bus voltage in the desired value.

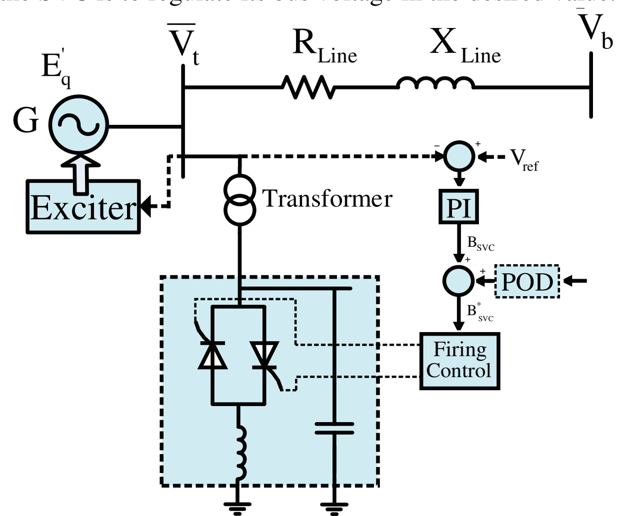


Fig. 1 A single machine infinite bus power system with an SVC

A. *Nonlinear Dynamic Model of the Power System with SVC*

As the first step, a nonlinear dynamic model for the examined system is derived by neglecting the resistance of all the components including generator, transmission line, and shunt transformer. For the work at hand, the IEEE Type-ST1A excitation system is considered. The dynamic model of the power system in Fig. 1 would be as follows [21]. The effect of SVC is incorporated in the main equations of the system.

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

$$\dot{\omega} = \frac{P_m - P_e - P_D}{M} \tag{2}$$

$$\dot{E}'q = \frac{(-E_q + E_{fd})}{T'_{do}} \tag{3}$$

$$\dot{E}_{fd} = \frac{-E_{fd} + K_A(V_{ref} - V_t)}{T_A} \tag{4}$$

where

: Rotor angle of synchronous generator in radians

: 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

B. *Linear Dynamic Model of the Power System with SVC*

The linear Heffron-Philips model of an SMIB system including SVC can be established by linearizing the nonlinear model around a nominal operating point.

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{5}$$

$$\Delta\dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \tag{6}$$

$$\Delta\dot{E}'_q = \frac{(-\ E_q +\ E_{fd})}{T'_{do}} \tag{7}$$

$$\Delta\dot{E}_{fd} = \frac{-\ E_{fd} + K_A(\ V_{ref} -\ V_t)}{T_A} \tag{8}$$

Fig. 2 demonstrates the transfer function model for the modified Heffron-Phillips model of the SMIB system with SVC.

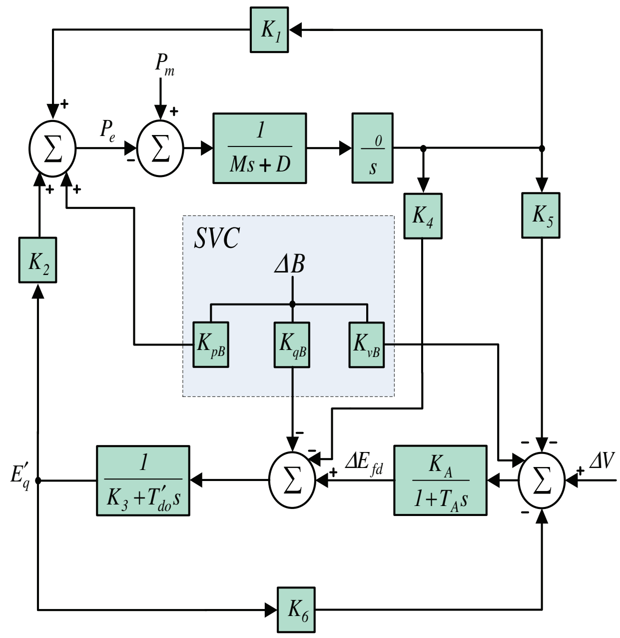


Fig. 2 Heffron-Phillips model of the investigated power system

C. Heffron-Phillips Model Constants

For the power system, the nominal operating point is set to the given values.

$$P_e = 0.8\,pu,\;\; Q_e = 0.15\,pu,\; V_t = 1\,pu$$

The Heffron-Phillips model constants are computed based on the values of the nominal operating point and some other system data which are reported in the Appendix A. Also the parameters of SVC are given in the Appendix B. Finally, Appendix C presents the entire Heffron-Phillips model constants computed for the system model depicted in Fig. 2.

III. Low Frequency Damping Controllers Design

With the aim of damping the low frequency oscillations, three sorts of damping controllers are designed and compared with each other. As mentioned earlier, the equivalent susceptance of the SVC namely B_{SVC}, provides a control signal to achieve a better damping of oscillations. In the following sections, each controller would be discussed in detail.

A. Conventional Proportional-Integral (PI) Controller

It is a well-known fact that the power system oscillations occur due to the lack of damping torque at the generators rotors. Hence, the damping controllers are designed to provide an extra electrical torque in phase with the speed deviation so as to increase the damping of oscillations [1]. Fig. 3 displays the conventional PI controller structure. It can be observed that the first block compares the actual generator rotor speed with its reference value. In the sequel, the error is let to pass through a PI controller to properly alter the equivalent susceptance of the SVC. Different techniques have been applied to design PI controllers such as try and error method, pole-placement, Ziegler-Nichols and so forth. In this study, try and error method is used to set suitable values for PI controller gains.

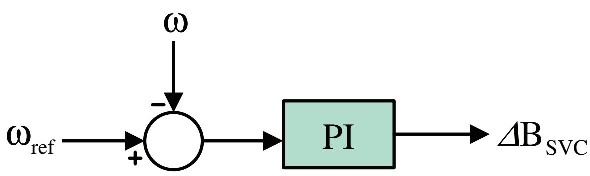


Fig. 3 Conventional PI damping controller

B. Auxiliary Fuzzy Logic Damping Controller

Although the PI controllers offer simplicity and ease of design, their performance depreciates when the system conditions vary in a wide range or large disturbances occur. As a result, to guarantee 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 SVC input. FLC generates the required small change for the equivalent susceptance of the SVC to control the magnitude of the terminal voltage. For the presented FLC, the centroid defuzzyfication technique is used. Fig. 4 depicts the FLC structure. Here, a two–input, one–output FLC is considered. The input signals are angular speed deviation (   ) and load angle deviation (   ) and the resultant output signal is the change of equivalent susceptance of the SVC.

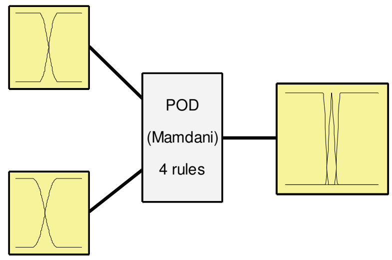


Fig. 4 Fuzzy logic damping controller structure

Membership functions of the input and output signals are shown in Fig. 5. Two linguistic variable are assigned 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).

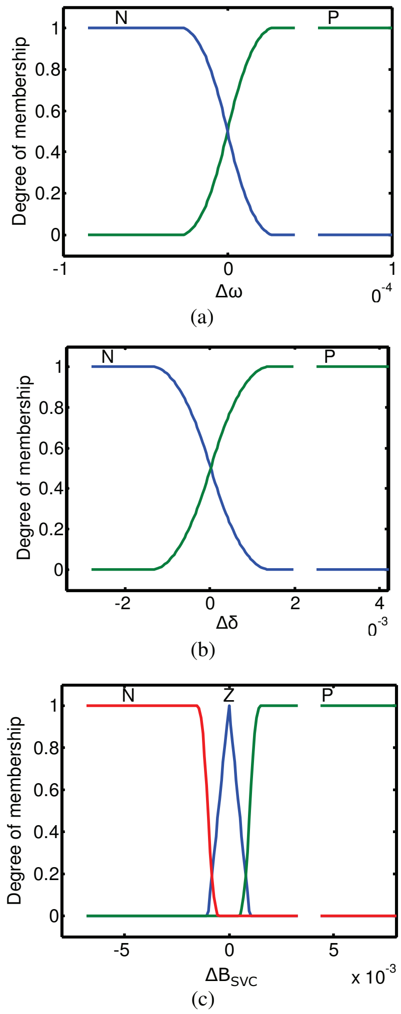


Fig. 5 (a), (b) inputs membership function, (c) output membership function

The rules used for the FLC are chosen as follows:

If is P **and** is N, **then** Δ is Z.
If is P **and** is P, **then** Δ is P.
If is N **and** is P, **then** Δ is Z.
If is N **and** is N, **then** Δ is N.

C. ANFIS Based Damping Controller

ANFIS was firstly proposed by [22]. In fact the ANFIS system is the same as the conventional fuzzy systems except that computations at each stage is carried out by a layer of hidden neurons and the neural network's learning ability is provided to enhance the system knowledge. In this work, the structure of the ANFIS based controller is a linear Sugeno type fuzzy inference system with the parameters inside the FIS decided by the neural-network hybrid method that combines the least-squares estimator and the gradient descent method. Fig. 6 shows a 2-input ANFIS with 4 rules. Two membership functions are assigned for each input. The outputs of the inference system are linear membership functions. The rules are in the following form:

Rule i: IF is A_j AND is B_j

$$\text{THEN } y = f_j = C_0^j + C_1^j \Delta\omega + C_2^j \Delta\delta$$

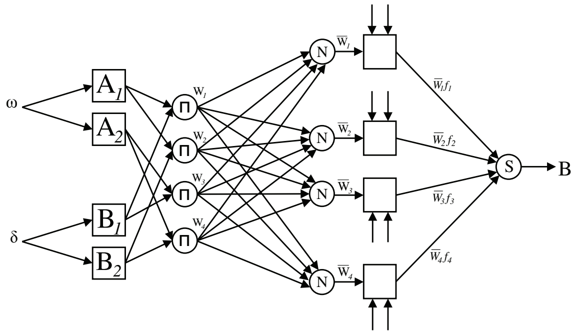


Fig. 6 Proposed ANFIS based damping controller structure

The ANFIS is designed by taking angular speed deviation ( ) and load angle deviation ( ) as the inputs. The output stabilizing signal is computed using the fuzzy membership functions depending on these variables. The initial membership function for the ANFIS is the same as FLC. Then the ANFIS is utilized to optimize the membership functions and to generate the proper precondition parameters of output linear membership functions. Fig. 7 demonstrates the output of ANFIS controller versus its inputs.

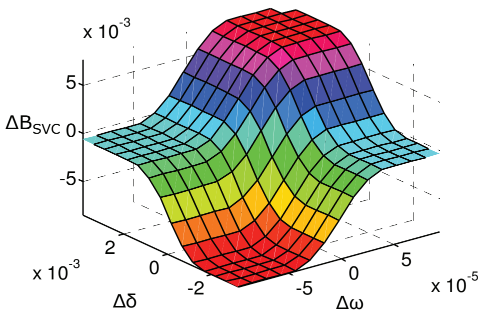
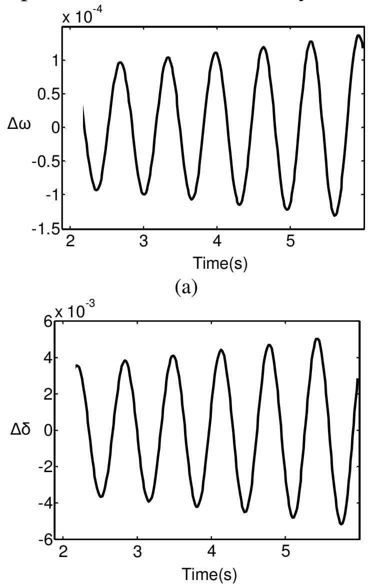


Fig. 7 The rules surface for B_{SVC} controller

IV. Simulation Results

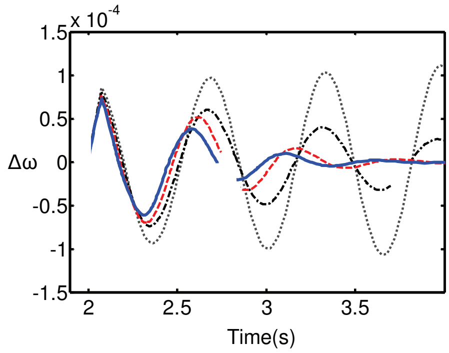
With the aim of assessing the proposed ANFIS based damping controller performance with the conventional PI and fuzzy logic damping controller, some useful simulations are performed. The disturbance simulated is a step change in mechanical power ($\Delta P_m = 0.01$) which occurs at t=2sec and lasts for 0.075 sec. At the outset, the SVC is not equipped with a damping controller. For this case, the angular speed deviation and also the load angle deviation responses are shown in Fig. 8. This figure discloses that when there is no damping controller, the power oscillations make the system unstable; consequently a supplementary damping controller is fundamentally required to improve the transient stability of the system.



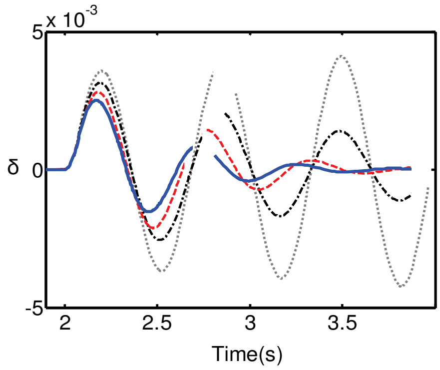
(b)

Fig. 8 (a), (b) Low frequency oscillations; no damping controller

In the following, simulations are carried out with the same contingency in mechanical power but the SVC has been equipped with a damping controller. Simulation results are displayed in Fig. 9. It can be deduced that the fuzzy logic controller exhibits better damping than the conventional PI controller. Moreover, it can be observed that the LFO excellent damping is achieved when the ANFIS based controller is considered. Likewise, system transient stability is increased when the SVC is equipped with the ANFIS based damping controller. Simulation results validate the efficiency of the proposed ANFIS based damping controller.



(a)



(b)

Fig. 9 (a), (b) Comparison of conventional PI and FLC with ANFIS in Low frequency oscillations damping; Solid (ANFIS), Dashed (FLC), Dash-Dotted (PI), Dotted (No controller)

V. CONCLUSION

This paper provides an exact survey to obtain a complete linearized Heffron-Phillips model for a single machine infinite bus power system incorporated with an SVC to analyze LFO damping with an auxiliary ANFIS based damping controller. A contingency in power system initiated power oscillations. In the following, three sorts of controllers, namely, the conventional PI, FLC and ANFIS based controller were designed to damp the system oscillations. A comparison between the controllers performance reveals that the FLC has superior performance and influence in transient stability enhancement and oscillations damping than its PI counterpart. Finally the system was armed with the developed ANFIS based controller. Simulation results show that the best of damping capability is achieved through the ANFIS based controller. Consequently, the ANFIS based damping controller would be a better option in the design of damping controllers.

APPENDIX A

POWER SYSTEM PARAMETERS

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, $\omega_0=2\pi f_0$

Excitation system:

$K_A=5$, $T_A=0.005$ s

Transmission line and transformer reactances:

$X_{Line}=0.4$ pu

APPENDIX B

THE SVC PARAMETERS

$B_C=0.2$ pu; $B_L=-0.4$ pu;

APPENDIX C

HEFFRON-PHILLIPS MODEL CONSTANTS

$K_1=1.9796$; $K_2=0.8539$; $K_3=1.1698$

$K_4=0.064$; $K_5=-0.0159$; $K_6=0.9424$

$K_{pB}=0.3088$; $K_{qB}=-0.0653$; $K_{vB}=-0.0227$

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