Improvement of Transient Voltage Response Using PSS-SVC Coordination Based on ANFIS Algorithm in a Three-Bus Power System

by I Made Ginarsa

Improvement of Transient Voltage Response Using PSS-SVC Coordination Based On ANFIS-Algorithm in a Three-Bus Power System

I Made Ginarsa, Agung Budi Muljono, I Made Ari Nrartha

Abstract—Transient voltage response appears in power system operation when an additional loading is forced to load bus of power systems. In this research, improvement of transient voltage response is done by using power system stabilizer-static var compensator (PSS-SVC) based on adaptive neuro-fuzzy inference system (ANFIS)-algorithm. The main function of the PSS is to add damping component to damp rotor oscillation through automatic voltage regulator (AVR) and excitation system. Learning process of the ANFIS is done by using off-line method. Where, data learning that used to train the ANFIS model are obtained by simulating the PSS-SVC conventional. The ANFIS model uses 7 Gaussian membership functions at two inputs and 49 rules at an output. Then, the ANFIS-PSS and ANFIS-SVC models are applied to power systems. Simulation result shows that the response of transient voltage is improved with settling time at the time of 4.25 s.

Keywords—Improvement, transient voltage, PSS-SVC, ANFIS, settling time.

I. INTRODUCTION

IMPROVEMENT of transient voltage response is one of concern some engineers in power system field. Improvement of transient voltage response of power systems has been done using additional PID controller based on adaptive neuro-fuzzy inference system (ANFIS)-algorithm [1]. Meanwhile, chaos and voltage collapse are nonlinear phenomena that exist in power systems due to critical loading. Chiang et al. developed the voltage collapse model and described both the physical explanation and computational consideration of this model. Static and dynamic models are used to detail the type of voltage collapse, wherein the static model is used before a saddle-node bifurcation. And, the dynamic model is employed after the bifurcation [2]. The Lyapunov exponent, which is used to measure how rapidly the two nearby trajectories separate from one another within the state space and broadband spectrum [3]. Within the range of loading conditions, the sensitivity of chaotic behavior makes power systems unpredictable after a finite time. In addition, the effectiveness of any control scheme is questionable within this range and should be re-evaluated based on state vector information. Some of controllers are proposed in order to reduce oscillation of power systems such as: power system stabilizer (PSS) based on neural network [9], proportional integral derivative-static var compensator (PID-SVC) coordination based on layered recurrent network [8], global control [10] or composite controller [4] [5] [11] [12].

Research of PSS and its application to improve the stability of power systems are done in recent years. A novel technique based on heuristic-dynamic-programming (HDP) method is used to damp low frequency oscillation in turbo generator. Where, the HDP is combination of dynamic programming and reinforcement learning to design nonlinear optimal power system stabilizer [13]. Tuning of PSS using feed-forward artificial neural network (ANN) in wide range operating conditions of single generator connected to infinite bus [14]. Design of PSS using pole placement technique with the emphasis on the frequency response characteristic [15]. Additional PID-loop combined by composite controller (CC) has been used to improve transient voltage response in power systems [11]. However, the response of this controller can be more improve especially at settling time by using another scheme control. Static var compensator (SVC) is an interesting research topics in power system field. There have been many methods was applied an ANFIS-algorithm has been successfully applied to control and suppress chaos and voltage collapse in power systems.

This research is focused on improving of transient voltage response using PSS-SVC based on ANFIS-algorithm. The PSS-SVC is used in this research because combination of the controllers are able to give a better response than CC-SVC or CC-PID-SVC. This paper is organized as follow: power system model which used in this research is introduced in Section II. The coordination of power system stabilizer and static var compensator based on ANFIS-algorithm are described in Section III. Next, some simulation results and analysis are presented in Section IV. Finally, conclusion is summarized in the last section.

II. POWER SYSTEM MODEL

A generic power system model for dynamic studies is described in this section. Single generator was expressed using a voltage (E'_{q0}) behind a direct reactance (x'_d). In this situation, the voltage magnitude was assumed to remain constant at the pre-disturbance value. This generator model connected to an infinite bus was derived firstly by de Mello and Concordia, as well as Kundur [16]. When a load is treated as a static load, the stator resistance and saturation are neglected, the system is operated in balanced condition.

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The generator supplies the load through the infinite bus. The armature current flows from the generator to the load and this current appears electrical torque on the stator winding, and vice versa. The flux of the rotor winding produces the mechanical torque in the rotor-stator circuit. The rotor speed follows the synchronous speed when the rotor speed is constant relatively. Meanwhile, if imbalance energy occurs in this rotor-stator circuit, the rotor speed will accelerate or decelerate. Furthermore, the swing phenomenon is occurred the generator system. This single generator connected to infinite bus model is shown in Fig. 1, and is developed from the work of Chiang et al. [2]. This model represents the system as a synchronous generator that supplies electrical power to a local dynamic load and combined by a shunt capacitor (Bus 2). Furthermore, Bus 2 is connected by a weak tie line to an external system or infinite bus (Bus 3). Where, the infinite bus is represented as follows:

$$V_0^{'} = \frac{V_0}{\sqrt{\left(1 + C^2 Y_0^{-2} - 2CY_0^{-1}\cos\theta_0\right)}} \tag{1}$$

$$Y_0^{'} = Y_0\sqrt{\left(1 + C^2 Y_0^{-2} - 2CY_0^{-1}\cos\theta_0\right)} \tag{2}$$

$$\theta_0^{'} = \theta_0 + \arctan\left(\frac{CY_0^{-1}\sin\theta_0}{1 - CY_0^{-1}\cos\theta_0}\right) \tag{3}$$

By using the variables and parameters on Table 1, the $V_0^{'}$, $Y_0^{'}$, $\theta_0^{'}$ are obtained as follows: $V_0^{'} = 2.5$ pu, $Y_0^{'} = 8.0$ pu, $\theta_0^{'} = -0.209$ rad [2]. Thus, power system equations are defined as follows:

$$\dot{\delta}_m = \Delta\omega \tag{4}$$

$$\begin{aligned} \Delta\dot{\omega} \;=\; & \frac{1}{M}\left[-D\Delta\omega + P_m + V_m{}^2 Y_m \sin(\theta_m)\right. \\ & \left. + V_m V Y_m \sin(\delta - \delta_m - \theta_m) + \Delta T_e\right] \end{aligned} \tag{5}$$

$$\begin{aligned} \dot{\delta} \;=\; & \frac{1}{K_{q\omega}}\left[-K_{qv}V - K_{qv2}V^2\right. \\ & \left. + Q - Q_0 - Q_1\right] \end{aligned} \tag{6}$$

$$\begin{aligned} \dot{V} \;=\; & \frac{1}{TK_{q\omega}K_{pv}}\left[K_{p\omega}K_{qv2}V^2 + (K_{p\omega}K_{qv}\right. \\ & - K_{q\omega}K_{pv})V + K_{p\omega}(Q_0 + Q_1 - Q) \\ & \left. - K_{q\omega}(P_0 + P_1 - P) + u(\Delta\omega)\right] \end{aligned} \tag{7}$$

TABLE I

POWER SYSTEM PARAMETER VALUES [2]

Y_0	Y_m	V_0	V_m	θ_0	θ_m	P_m	M	D
20.0	5.0	1.0	1.0	−5.0	−5.0	1.0	0.3	0.05
$K_{p\omega}$	K_{pv}	$K_{q\omega}$	K_{qv}	K_{qv2}	C	P_0	Q_0	T
0.4	0.3	−0.03	−2.8	2.1	12.0	0.6	1.3	8.5

All parameter values are in pu except for angles, which are in degs

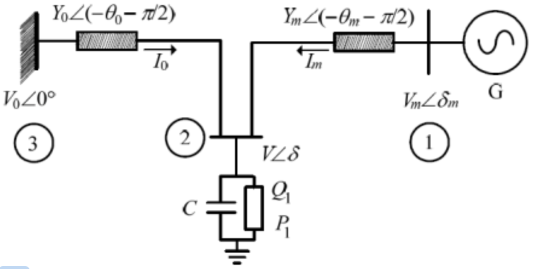

Fig. 1. Single-line diagram of a three-bus power system [2]

where the K_{pv}, K_{qv}, K_{qv2}, T, $K_{p\omega}$ and $K_{q\omega}$ parameters are the real load constant due to voltage deviation, reactive load constant due to voltage deviation, reactive load constant due to voltage square deviation, time constant, real load constant due to frequency deviation and reactive load constant due to frequency deviation, respectively. The variables P and Q are calculated using Eqs. (8) and (9), respectively. The parameters P_1, Q_1 and D are the real load, reactive load and damping constant. The parameter $u(\Delta\omega)$ is implemented as a control signal of the power systems. And, the parameter (ΔT_e) is an electrical torque damping component that produced by a PSS and an excitation system. The variables δ_m, $\Delta\omega$, δ and V are the power angle, rotor speed deviation, angle and magnitude of the voltage.

$$\begin{aligned} P \;=\; & -V_0^{'}VY_0^{'}\sin(\delta + \theta_0^{'}) \\ & -V_m V Y_m \sin(\delta - \delta_m + \theta_m) \\ & +\left[Y_0^{'}\sin(\theta_0^{'}) + Y_m\sin(\theta_m)\right]V^2 \end{aligned} \tag{8}$$

$$\begin{aligned} Q \;=\; & V_0^{'}VY_0^{'}\cos(\delta + \theta_0^{'}) \\ & +V_m V Y_m \cos(\delta - \delta_m + \theta_m) \\ & -\left[Y_0^{'}\cos(\theta_0^{'}) + Y_m\cos(\theta_m)\right]V^2 \end{aligned} \tag{9}$$

III. COORDINATION OF PSS AND SVC BASED ON ANFIS

In order to get the proposed controller is able to improve transient voltage response. Step by step processes should be done. First step was to design conventional controller such as power system stabilizer (PSS) and static var compensator (SVC) conventional. Second step was to examine the conventional controller in power systems and to collect data training from the conventional controller. Third step was to train PSS and SVC based on ANFIS-algorithm by using the data training that were obtained from the conventional controller. And, final step was to apply the proposed controller to power systems. In this final step, the performance of the proposed controller was tested and examined. Also, numerical and graphical data were collected in this simulation to analysis the performance of the proposed controller.

A. *Power system stabilizer design*

The basic function of a power system stabilizer (PSS) is to add damping to the generator rotor oscillation by controlling its excitation system using auxiliary stabilizing signal(s) [16]. To provide damping, PSS must produce a component of

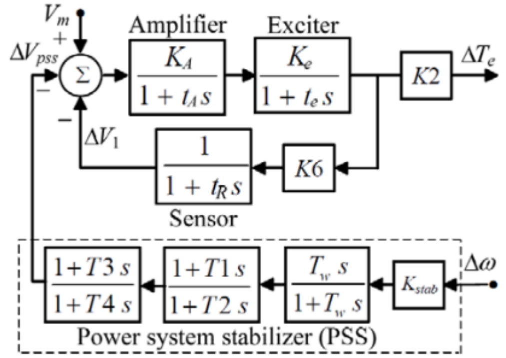

Fig. 2. PSS and excitation system block diagrams

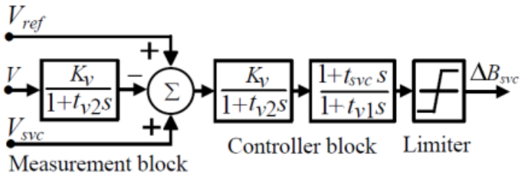

Fig. 3. Static var compensator block diagram

electrical torque in phase with rotor speed deviation. The block diagrams of PSS and excitation system are shown in Fig. 2. In this research rotor speed deviation ($\Delta\omega$) was used as an PSS input. And, the output was an additional control signal (ΔV_{pss}). This output signal was used to modulate excitation system and to produce damping component of electrical torque (ΔT_e). Then, the damping component of electrical torque was applied to damp rotor oscillation of the generator.

B. *Static var compensator design*

Static var compensator (SVC) is shunt-connected generator and/or absorber whose output is varied so as to control a specific or more parameters of electric power systems. The term static is used to indicate that SVC, unlike synchronous compensator has no moving or rotating main component [16]. Let us start with SVC that was applied at bus k, and the reactive power was injected to bus k

$$Q_k = V_k^2 B_{svc} \tag{10}$$

where $B_{svc} = B_c - B_l$, B_{svc}, B_c and B_l are the SVC, capacitive and inductive susceptances, respectively. Dynamic equations of SVC is written as follows [17]:

$$\begin{aligned}\Delta\dot{B}_{svc} \;=\; & \frac{1}{t_{svc}}\left[\left(1-\frac{t_{v1}}{T_{v2}}\right)\Delta V_{r-svc}\right.\\ & \left.-\Delta B_{svc}-\frac{K_v t_{v1}}{t_{v2}}\Delta V_{t-svc}\right]\\ & +\frac{K_v t_{v1}}{t_{v2}t_{svc}}\left[\Delta V_{ss-svc}+\Delta V_{ref}\right]\end{aligned} \tag{11}$$

where t_{svc}, t_{v1}, t_{v2}, K_v, ΔV_{ss-svc}, ΔV_{r-svc}, ΔV_{t-svc} and ΔV_{ref} are the SVC time constant, time constant 1, time constant 2, SVC gain, SVC voltage at steady state, difference of reference–SVC voltage, difference of terminal–SVC voltage and reference voltage, respectively. And parameter values of SVC for the t_{svc}, t_{v1}, t_{v2} and K_v were 70.0, 32.309, 400.0 and 30.0, respectively. Block diagram of the SVC is shown in Fig. 3.

C. *PSS-SVC based on ANFIS-algorithm design*

A PSS-SVC based on ANFIS-algorithm was used in this research consist of two parts such as: PSS based on ANFIS-algorithm and SVC based on ANFIS-algorithm, respectively. While, rotor speed deviation ($\Delta\omega$) was transformed into discrete mode using zero order hold (ZOH) component and the rotor speed deviation was taken as an input 1 of PSS-ANFIS. Next, the rotor speed deviation was delayed using unit delay and the delay signal was taken as an input 2 of the PSS based on ANFIS. Furthermore, time sampling of the controller was taken at 0.01 s. This PSS based on ANFIS produces a single output signal as a (ΔV_{pss}). The (ΔV_{pss}) signal was used to modulate the excitation system through the automatic voltage regulator (AVR) and to produce additional electrical torque (ΔT_e) in electrical mode. This additional electrical torque was represented as additional damping component. Next, the additional damping component was used to damp rotor oscillation of generator in mechanical mode. Block diagram of the proposed controller applied to a power system is shown in Fig. 4.

The training processes were performed by using off-line stage with 2000 data points. Seven linguistic variables were used to describe each of the input variables such as: negative very high (NV), negative high (NH), negative low (NL), zero (ZE), positive low (PL), positive high (PH) and positive very high (PV), respectively. Linguistic variables and membership function of the rotor speed deviation are shown in Fig. 5. In this research we used Gaussian membership function for two inputs (input 1 and input 2). Membership functions were used to define the degree of membership of input variables. A Gaussian membership function was specified by two parameters c and τ. Where, c and τ represent the membership function's center and spread, respectively. This parameters were obtained automatically trough training processes. We used hybrid algorithm [18] at the training processes. Where the hybrid algorithm is a combination of back-propagation and least squares estimation algorithms.

Input-output control surface of PSS based on ANFIS-algorithm is shown in Fig. 6. Fig. 6 shows the nonlinear relationship of input 1 ($\Delta\omega$) and input 2 ($\Delta\omega$ with a unit delay) against the output of PSS and excitation system (ΔT_e).

Controlling nonlinear oscillation phenomena such as chaos, chaos to voltage collapse and equilibrium point have been interest topic of research in recent years. Research topic of controlling chaos by using composite controller (ANFIS CC) in power systems was explained in Ref. [11] [12]. Unfortunately, the topic of controlling chaos was omitted in this research because of limited space.

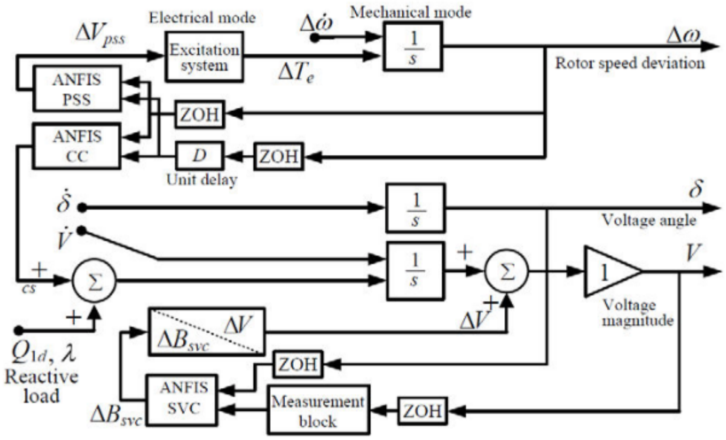

Fig. 4. Application of the proposed controllers to power systems

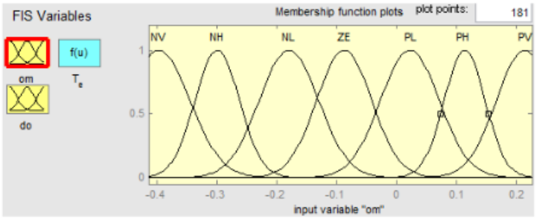

Fig. 5. Linguistic variables and membership functions of the ($\Delta\omega$)

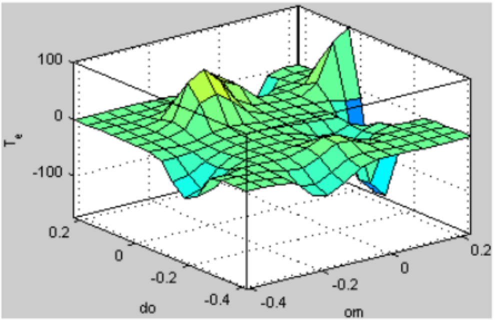

Fig. 6. Input-output control surface of PSS based on ANFIS-algorithm

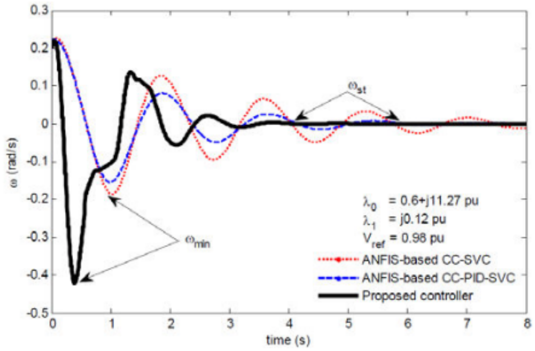

Fig. 7. Improvement of the ($\Delta\omega$) response by the proposed controller

IV. RESULT AND ANALYSIS

Proposed controller is illustrated and examined by considering a high load in a three-bus power system. Simulation results were obtained by Matlab/Simulink Ver. 7.6.0 324 on an Intel Core 2 Duo E6550 2.33 GHz personal computer. Load bus was disturbed by additional reactive load (Q_{1d}) and the rotor speed deviation as an output was observed. Effectiveness of the proposed controller was examined using additional reactive load at the values of $j0.10$, $j0.11$, $j0.12$ pu, and an initial load at 0.6+$j11.27$ pu. The voltage reference was taken at 0.98 pu. Rotor speed deviation ($\Delta\omega$) of ANFIS-based CC-SVC, CC-PID-SVC and the proposed controller responses when the additional load at $j0.12$ pu are shown in Fig. 7. The improvement of the rotor speed deviation response is assessed by settling time of respective controller. The settling time was achieved at time of 11.47, 5.98 and 4.02 s for ANFIS-based CC-SVC, ANFIS-based CC-PID-SVC and the proposed controller when load bus was forced by additional reactive load at the value of $j0.12$ pu.

Furthermore, performances of the respective controller for rotor speed deviation are listed in Table II. Also, Table II shows the settling time of proposed controller was shorter (3.31 and 3.36 s) than the settling time of the other controllers (9.84 and 9.97 s) when the power systems were forced by the additional reactive load at $j0.10$ and $j0.11$ pu, respectively. The PSS and excitation systems were able to support electrical torque at the values of 0.5464, 0.5464 and 0.5474 pu to damp the rotor oscillation for additional reactive load at $j0.10$, $j0.11$ and $j0.12$ pu, respectively. The PSS produced the maximum output voltage (ΔV_{pm}) at the values of 2.2571, 2.2735 and

2.2943 $\times 10^{-3}$ pu for additional reactive load at $j0.10$, $j0.11$ and $j0.12$ pu, respectively.

Performances of the respective controller for load voltage response are listed in Table III. At First scenario, an additional load was forced to load bus at the value of $j0.10$ pu. The susceptance of SVC (B_{svc}) was at the values of $j0.1185$, $j0.1183$, $j0.1183$ and $j0.0335$ pu for LC-SVC, ANFIS-based CC-SVC, ANFIS-based CC-PID-SVC and the proposed controller, respectively. The respective B_{svc} values were used to maintain the load voltage at around voltage setting (0.98 pu). At this condition the SVC supplied additional reactive power to the network was at the values of $j0.1129$, $j0.1137$, $j0.1137$ and $j0.0321$ pu. And, the additional voltage (ΔV) that produced by the SVC was at the values of 4.0152, 4.0098, 4.0121 and 1.1356 $\times 10^{-3}$ pu, respectively. In this research, the load voltage minimum (V_{min}) was obtained at the values of 0.9265, 0.8963, 0.9430 and 0.9135 pu for LC-SVC, ANFIS-based CC-SVC, ANFIS-based CC-PID-SVC and the proposed controller, respectively. The settling time was obtained at the values of 16.24, 12.76, 7.58 and 3.51 s for LC-SVC, ANFIS-based CC-SVC, ANFIS-based CC-PID-SVC and the proposed controller, respectively.

Second scenario, in this scenario the additional load was increased to $j0.11$ pu. The susceptance of SVC was obtained at the values of $j0.1297$, $j0.1297$, $j0.1297$ and $j0.0452$ pu for LC-SVC, ANFIS-based CC-SVC, ANFIS-based CC-PID-SVC and the proposed controller, respectively. In this condition, the SVC supported additional reactive power to the network at the values of $j0.1234$, $j0.1234$, $j0.1235$ and $j0.0322$ pu. And, the additional voltage that produced by the SVC was at the values of 4.3941, 4.3941, 4.3950 and 1.5302 $\times 10^{-3}$ pu, respectively.

Third scenario, the additional reactive load was increased again to $j0.12$ pu. The susceptance of SVC was obtained at the values of $j0.1410$, $j0.1411$, $j0.1410$ and $j0.0570$ pu for LC-SVC, ANFIS-based CC-SVC, ANFIS-based CC-PID-SVC and the proposed controller, respectively. The additional reactive power supplied by the SVC to the network was at the value of $j0.1341$, $j0.1342$, $j0.1354$ and $j0.0546$ pu. And, the SVC device produced additional voltage at 4.7776, 4.7815, 4.7793 and 1.9329 $\times 10^{-3}$ pu, respectively. When the additional load is increased, the susceptance of SVC is needed to increase also to support the load voltage remain in around the setting value.

Proposed controller is used to improve transient voltage response at critical loading of a three-bus power system by decreasing the settling time. Four controller types were compared such as: Linear controller (LC-SVC), ANFIS-based CC-SVC, CC-PID-SVC and PSS-SVC based on ANFIS-algorithm (proposed controller). Fig. 8 shows the settling times of each controllers were at 12.5, 9.5, 7.01 and 4.25 s for LC-SVC, ANFIS-based CC-SVC, CC-PID-SVC and the proposed controller, respectively. From the settling time point of view its is shown that the proposed controller makes the load voltage reach to the steady state (equilibrium point) quickly. The load voltage oscillated in 3 cycles only, then this oscillation damped to steady state rapidly at 0.98 pu. On the contrary, the load voltage of the other controllers oscillated in 5 cycles or more. The performances of respective controller are assessed from their temporal responses. The proposed controller gives better performance than the others. Where, the settling time of the proposed controller was at time of 4.25 s when the additional load at $j0.12$ pu.

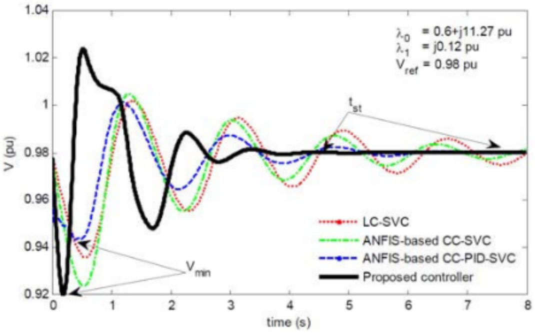

Fig. 8. Improvement of load voltage (V) responses by the proposed controller

TABLE II
PERFORMANCE OF PROPOSED CONTROLLER COMPARED TO OTHER CONTROLLER

Controller	λ_1 $\times j$ (pu)	ΔV_{pm} $\times 10^{-3}$(pu)	ΔT_e (pu)	ω_{min} (rad/s)	ω_{st} s
CC-SVC	0.10	-	-	– 0.184	15.12
	0.11	-	-	– 0.183	14.83
	0.12	-	-	– 0.206	11.47
CC-PID-SVC	0.10	-	-	– 0.158	9.84
	0.11	-	-	– 0.162	9.97
	0.12	-	-	– 0.164	5.98
Proposed cont.	0.10	2.2571	0.5464	– 0.37	3.31
	0.11	2.2735	0.5464	– 0.38	3.36
	0.12	2.2943	0.5474	– 0.41	4.02

V. CONCLUSION

Improvement of transient voltage response is a focus topic in this research. The improvement scheme is done by using power system stabilizer-static var compensator (PSS-SVC) based on ANFIS-algorithm (proposed controller). Where the PSS is used to add damping component to the rotor speed oscillation. The proposed controller is constructed by using data from the conventional controller. Parameters of the proposed controller are obtained using off-line method with least squared estimation and backpropagation optimization algorithm. Seven linguistic variables with Gaussian membership functions are used to implement of proposed controller. The settling time of the rotor speed deviation is achieved at the time of 4.02 s for the proposed controller when power systems is disturbed by additional reactive load at $j0.12$ pu. The settling time of the load voltage is achieved at the times of 16.27, 12.05, 7.01 and 4.25 s for LC-SVC, CC-SVC, CC-PID-SVC and the proposed controller, respectively. The simulation result shows that the proposed controller is better than the other controllers, where the settling time of the proposed controller is shorter than the others.

TABLE III
PERFORMANCE OF PROPOSED CONTROLLER FOR LOAD VOLTAGE

Controller	λ_1 $\times j$ (pu)	B_{svc} $\times j$ (pu)	Q_{svc} $\times j$ (pu)	V (pu)	ΔV $\times 10^{-3}$ (pu)	V_{min} (pu)	V_{st} (s)
LC-SVC	0.10	0.1185	0.1129	0.98003	4.0152	0.9265	16.24
	0.11	0.1297	0.1234	0.98001	4.3941	0.9364	17.34
	0.12	0.1410	0.1341	0.98001	4.7776	0.9453	16.27
CC-SVC	0.10	0.1183	0.1137	0.98000	4.0098	0.8963	12.76
	0.11	0.1297	0.1234	0.98000	4.3941	0.9253	15.37
	0.12	0.1411	0.1342	0.98006	4.7815	0.9362	12.05
CC-PID-SVC	0.10	0.1183	0.1137	0.98001	4.0121	0.9430	7.58
	0.11	0.1297	0.1235	0.98001	4.3950	0.9172	9.68
	0.12	0.1410	0.1354	0.98002	4.7793	0.9435	7.01
Proposed controller	0.10	0.0335	0.0321	0.98001	1.1356	0.9135	3.51
	0.11	0.0452	0.0432	0.98002	1.5302	0.9114	3.74
	0.12	0.0570	0.0546	0.98004	1.9329	0.9202	4.25

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