Controlling Voltage Collapse using ANFIS-based Composite Controller-SVC in Power Systems

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***Abstract*—Voltage collapse appears in critical load power systems as a nonlinear phenomenon due to lack of reactive power. Voltage collapse causes black out problem in power system networks, therefore its problem should be prevented in order to operate of the systems continually . In this research, ANFIS-based composite controller (ANFIS-based CC-SVC) was proposed to solve this problem. The ANFIS-based was chosen because its computation complexity was more efficient than Mamdani fuzzy logic controller. Three-bus power systems were used to validate performance of proposed controller. An additional reactive load at $j0.02$ pu was forced to load bus in order to examine the effectiveness of the proposed controller. This controller was able to prevent voltage collapse and maintain bus voltage to setting value. Moreover, the settling time and increasing of the load voltage were achieved at time of 5.52 s and value of 0.0118 pu, respectively.**

***Index Terms*—Voltage collapse, power system control, ANFIS, composite controller-SVC, load voltage maintain.**

I. INTRODUCTION

Load demand in a modern power system has grown up rapidly in recent decade. On the contrary, increment of power plants and transmission lines being built are very slow due to economical and environmental constrains. This situation will make power systems operate in critical mode at the boundary of voltage stability region. Lack of reactive power on critical load causes voltage collapse phenomenon exists in power systems. Chiang et al. [1] developed a fundamental model of voltage collapse in power systems and described both physical explanation and computational consideration of this problem. Static model was used before a saddle-node bifurcation, while dynamic model was employed after a bifurcation [1], [2]. Furthermore, nonlinear phenomena including bifurcation, chaos and voltage collapse occurred in a power system model. The problems of control and suppress of the presence of nonlinear phenomena in the power systems were addressed in these papers [3], [4]. Meanwhile, definition of voltage collapse and procedure of power system operation to prevent voltage collapse phenomenon were given in [5].

Nonlinear autoregressive moving average-neural networks controller (NARMA-NN) has been successfully applied to control chaos and voltage collapse in power systems [6]. Meanwhile, static var compensator (SVC) application is an attractive topic of research in power system engineering. SVC placement optimally using normal form analysis method was applied to maintain voltage stability of power systems [7]. While, adaptive neuro-fuzzy inference systems (ANFIS) technology is a combination of neural networks and fuzzy inference systems. This technology has been applied in power system control, including ANFIS-based CC successfully to control chaos [8] and ANFIS-based CC-SVC to control chaos and voltage collapse in power systems. In addition, an ANFIS-based SVC has been used to control reactive power balanced in order to maintain the load voltage [9] and an ANFIS-based CC-SVC with an additional PID-loop has been used to improve transient voltage response in power system operation [10], [11].

In this paper, we focus on controlling voltage collapse in power systems using ANFIS-based CC-SVC with an additional PID-loop. The ANFIS method was used in this research because its computational complexity was more effective than Mamdani fuzzy inference system. Whilst, the PID controller was chosen because it was simple and easy to be implemented. And, controller parameters were automatically updated by off-line training.

This paper is organized as follows: the model of power systems is explained in Section II. The ANFIS-based CC-SVC with an additional PID-loop design is depicted in Section III. Next, the simulation results and analysis are presented in Section IV. Finally, the conclusion is provided in the last section.

II. POWER SYSTEM MODEL

A. Single Machine Model

A synchronous machine was modeled as a voltage (E'_{q0}) behind a direct reactance (x'_d). The voltage magnitude was assumed as remaining constant at the pre-disturbance value. De Mello and Concordia, as well as Kundur derived this model of a machine connected to an infinite bus [12]. The machine was connected to the infinite bus and supplied the load. Then the armature current flowed from the machine to the load. This current caused electrical torque on the stator winding, and vice versa. The mechanical torque was produced by the flux through the rotor winding. When there was imbalanced

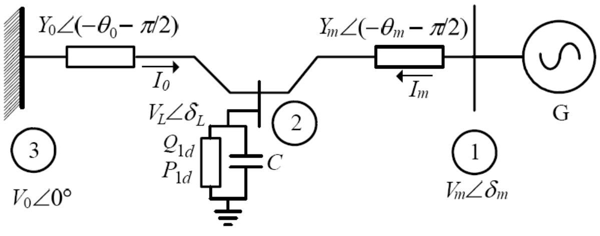

Fig. 1. Single-line diagram of three-bus power systems

energy, the rotor speed accelerated or decelerated, which can be expressed by the following equation

$$\dot{\omega}_m = \frac{1}{M}\left(T_m - T_e - D\omega_m\right) \tag{1}$$

where T_m, T_e, ω_m, D and M are the mechanical torque, electrical torque, rotor speed, damping constant and inertia constant, respectively.

B. Three-bus Power Systems

This system model was developed from the work of Chiang et al. [1], as shown in Fig. 1. This model represents the system as one synchronous machine that supplies power to a local dynamic load with a shunt capacitor (Bus 2) connected by a weak tie line to an external system (Bus 3). The Thevenin equivalent circuit with a capacitor is represented as follows:

$$V_0^{'} = \frac{V_0}{\left(1 + C^2 Y_0^{-2} - 2CY_0^{-1}\cos(\theta_0)\right)^{0.5}} \tag{2}$$

$$Y_0^{'} = Y_0\left(1 + C^2 Y_0^{-2} - 2CY_0^{-1}\cos(\theta_0)\right)^{0.5} \tag{3}$$

$$\theta_0^{'} = \theta_0 + \arctan\left(\frac{CY_0^{-1}\sin(\theta_0)}{1 - CY_0^{-1}\cos(\theta_0)}\right) \tag{4}$$

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

$$\dot{\delta_m} = \omega_m \tag{5}$$

$$\begin{aligned}\dot{\omega_m} \;=\; & \frac{1}{M}\left[-D\omega_m + P_m + {V_m}^2 Y_m \sin(\theta_m)\right. \\ & \left. + V_m V_L Y_m \sin(\delta_L - \delta_m - \theta_m)\right]\end{aligned} \tag{6}$$

$$\begin{aligned}\dot{\delta_L} \;=\; & \frac{1}{K_{q\omega}}\left[-K_{qv}V_L - K_{qv2}V_L^2\right. \\ & \left. + Q - Q_0 - Q_{1d}\right]\end{aligned} \tag{7}$$

$$\begin{aligned}\dot{V_L} \;=\; & \frac{1}{TK_{q\omega}K_{pv}}\left[K_{p\omega}K_{qv2}V_L^2 + (K_{p\omega}K_{qv}\right. \\ & -K_{q\omega}K_{pv})\,V_L + K_{p\omega}\left(Q_0 + Q_{1d} - Q\right) \\ & \left. -K_{q\omega}\left(P_0 + P_{1d} - P\right) + u(\omega_m)\right]\end{aligned} \tag{8}$$

where the variables δ_m, ω_m, δ_L, V_L, P and Q are the power angle, rotor speed, angle, magnitude of the voltage at the load bus, real power and reactive power, respectively. The variables P and Q are computed using (9) and (10). The parameters P_{1d}, Q_{1d} and D are the real load, reactive load and damping constant, respectively. In this case, the parameter $u(\omega_m)$ was implemented as a control signal of the power systems.

TABLE I
POWER SYSTEM PARAMETER VALUES

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

$$\begin{aligned}P \;=\; & -V_0^{'}V_L Y_0^{'}\sin(\delta_L + \theta_0^{'}) \\ & -V_m V_L Y_m \sin(\delta_L - \delta_m + \theta_m) \\ & + \left[Y_0^{'}\sin(\theta_0^{'}) + Y_m\sin(\theta_m)\right] V_L^2\end{aligned} \tag{9}$$

$$\begin{aligned}Q \;=\; & V_0^{'}V_L Y_0^{'}\cos(\delta_L + \theta_0^{'}) \\ & +V_m V_L Y_m \cos(\delta_L - \delta_m + \theta_m) \\ & - \left[Y_0^{'}\cos(\theta_0^{'}) + Y_m\cos(\theta_m)\right] V_L^2\end{aligned} \tag{10}$$

III. ANFIS-BASED CC-PID-SVC DESIGN

A. Composite Controller Design

Two types of control law, namely linear controller and nonlinear (cubic) controller were combined to produce composite controller. The function of linear controller was to improve both static and dynamic stability margins. Meanwhile, the function of cubic controller was to avoid chaos, voltage collapse and to improve stability degree [3]. The formulation of linear and nonlinear feedback controller with measurement of ω_m and u, can be written as follows:

$$u = k_l\omega_m \tag{11}$$

$$u = k_n\left(\omega_m\right)^3 \tag{12}$$

Furthermore, composite controller can be expressed as a combination of linear and nonlinear feedback control. The closed loop of power system formulas are shown in (5)–(8) with the ω_m and u can be expressed as the following equation

$$u = k_l\omega_m + k_n\left(\omega_m\right)^3 \tag{13}$$

where variable ω_m is the rotor speed. Parameters u, k_l, k_n are the control signal, linear gain and nonlinear gain, respectively. Parameter values of the composite controller (CC) for the k_l and k_n were taken at 0.08 and 0.08, respectively.

B. PID Controller Design

PID controllers are being extensively used by industries due to their simple structure, which can be easily understood and implemented. Our main focus was to eliminate of steady state error as well as to improve the dynamic response. The elimination of steady state error could be realized by adding a pole at the origin using an integral controller. Transient

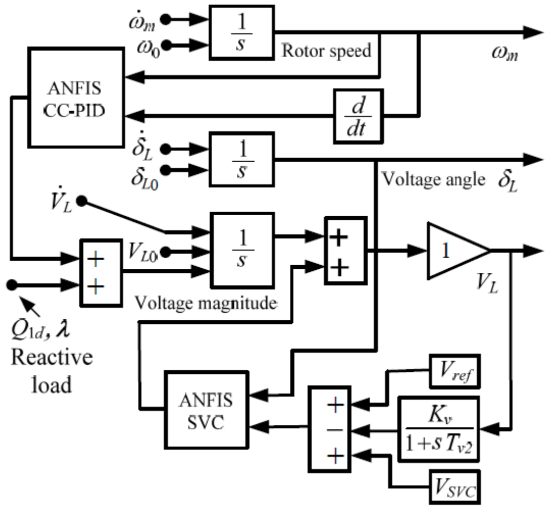

Fig. 2. Block diagram of the proposed controller applied to power systems

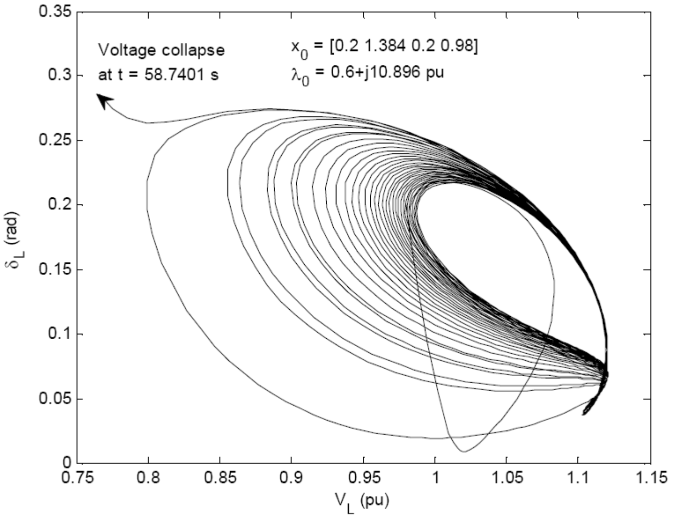

Fig. 3. Voltage collapse appears due to lack of reactive power

response improvement was achieved by the action of differential controller. The transfer function of PID controller [13] is expressed as follows:

$$G(s) = k_p + \frac{k_i}{s} + k_d s \tag{14}$$

where $G(s)$, k_p, k_i, k_d and s are the transfer function, proportional gain, integral gain, differential gain and Laplace operator, respectively. Parameter values of the PID-loop for the k_p, k_i and k_d were taken at 2.1995×10^{-2}, 3.9439×10^{-4} and 8.3×10^{-3}, respectively.

C. SVC Controller Design

Let us start with SVC that was applied at bus k, the reactive power was injected to bus k

$$Q_k = V_k^2 B_{SVC} \tag{15}$$

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 can be written as follows [14]:

$$\begin{aligned}\Delta\dot{B}_{SVC} \;=\; & \frac{1}{T_{SVC}}\left[\left(1-\frac{T_{v1}}{T_{v2}}\right)\Delta V_{r-SVC}\right. \\ & \left.-\Delta B_{SVC} - \frac{K_v T_{v1}}{T_{v2}}\Delta V_{t-SVC}\right] \\ & +\frac{K_v T_{v1}}{T_{v2}T_{SVC}}\left[\Delta V_{ss-SVC} + \Delta V_{ref}\right] \quad (16)\end{aligned}$$

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 and SVC voltage, difference of terminal and SVC voltage and reference voltage, respectively. Parameters of the SVC were obtained by using trial and error method. Parameter values of the T_{SVC}, T_{v1}, T_{v2} and K_v were obtained at 70.0, 12.96, 400.0 and 30.0, respectively. Meanwhile, block diagram of the proposed controller applied to power systems is shown in Fig. 2.

IV. SIMULATION RESULTS AND ANALYSIS

The effectiveness of the proposed controller was illustrated using three-bus power systems in critical loading. Then an additional reactive load as disturbance was forced to load bus. Simulation results were obtained by Matlab/Simulink V.7.6.0 324 on an Intel Core 2 Duo E6550 @ 2.33 GHz PC computer.

A. Power Systems without Controller

Power systems without any controller are very vulnerable to disturbances during operation under critical loading. Owing to ever-increasing of load demand, there is tremendous to operate power systems very near the edge of their stability boundaries. A disturbance and/or temporal overload cause a shift in a system parameter, such that a boundary crisis occurs leading to voltage collapse. Voltage collapse appears in power system due to lack of reactive power ($Q_{supplay}$). In this simulation, the voltage collapse occurred at time of 58.7401 s and initial load (parameter) at $\lambda_0 = 0.6 + j10.896$ pu. Initial condition of the $[\delta_m\ \omega_m\ \delta_L\ V_L]^T$ was at the values of [0.2 1.384 0.2 $0.98]^T$, respectively. Where T is matrix transpose.

Fig. 3 shows the voltage-angle trajectory of voltage collapse mechanism. The state trajectory oscillated on voltage-angle phase-plane then the trajectory splayed until 58.7401 s. Moreover, the trajectory disappeared from the system and voltage collapse occurred in power systems. Temporal response of voltage collapse phenomenon is shown in Fig. 4. The voltage oscillated in a few second, then the voltage declined toward zero at time of 58.7401 s.

B. Power Systems with the Proposed Controller

Performance of the proposed controller was evaluated by adding an additional reactive load (λ_1) at the value of $j0.02$ pu. In this simulation, critical loading of power systems and reference voltage of SVC were taken at the values of $0.6 + j11.29$ and 0.98 pu, respectively. An additional load were given at the value of $j0.02$ pu. The additional load was forced to load bus

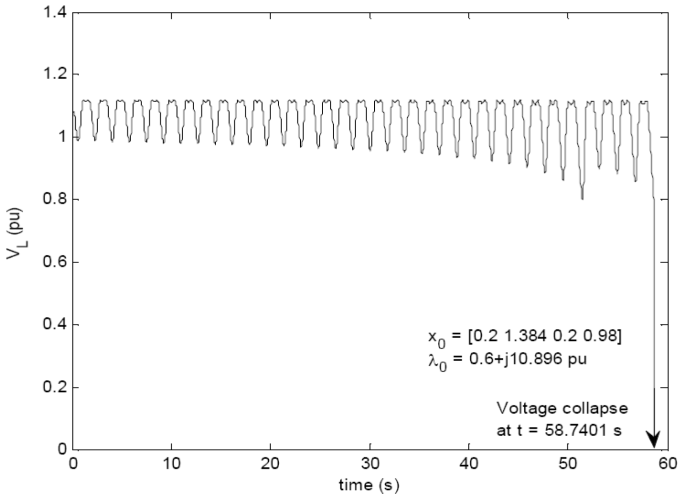

Fig. 4. Voltage collapse mechanism in power systems at time of 58.7401 s

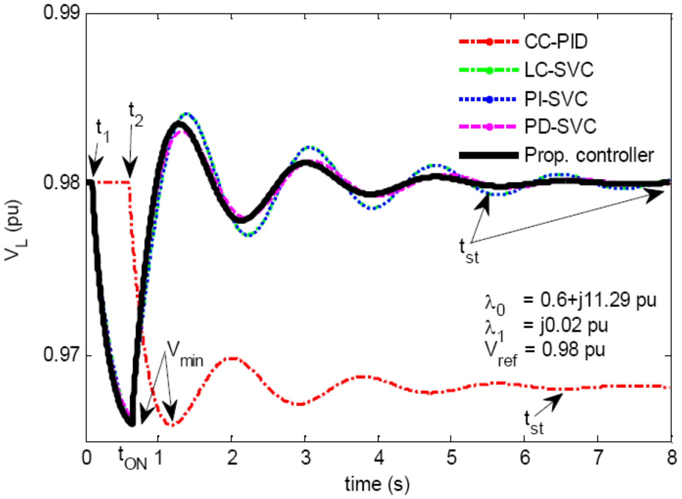

Fig. 5. Temporal responses of the load voltages (V_L) at $\lambda_1 = j0.02$ pu

TABLE II
COMPARISON OF THE CONTROLLER PERFORMANCES AT $\lambda_1 = j0.02$ PU

Control	V_{min} (pu)	t_{st} (s)	B_{SVC} (pu)	Q_{SVC} (pu)	ΔV (pu)	V_L (pu)
CC-PID	0.9660	6.37	-	-	-	0.9682
LC-SVC	0.9659	14.53	$j0.0224$	$j0.0215$	0.0119	0.9801
PI-SVC	0.9664	11.57	$j0.0224$	$j0.0215$	0.0119	0.9801
PD-SVC	0.9659	12.19	$j0.0224$	$j0.0215$	0.0118	0.9800
P. cont.	0.9660	5.52	$j0.0224$	$j0.0215$	0.0118	0.9800

λ_0=0.6+j11.29; λ_1=j0.02; V_{ref}=0.98 pu t_1=0.1; t_2=0.6; t_{ON}=0.65 s

for power systems equipped by SVC (t_1) and without any SVC (t_2) at times of 0.1 and 0.6 s, respectively. In order to control voltage collapse and maintain load voltage in power systems, SVC adjustment ON time (t_{ON}) was realized at time of 0.65 s. The minimum voltage (V_{min}), settling time (t_{st}), steady state V_L, load voltage increased (ΔV), SVC susceptance (B_{SVC}) and reactive power supplied by the SVC (Q_{SVC}) values were observed as the output data. The simulation results are listed in Table II.

The ANFIS-based CC-PID was not able to maintain the load voltage (V_L) to a setting value because its controller was not equipped by the SVC device (Fig. 5). The V_L was still low at the value of 0.9682 pu. On the contrary, the other controllers such as: LC-SVC, CC-SVC, PI-SVC, PD-SVC and proposed controller were able to maintain the V_L at the values of 0.9801, 0.9801, 0.98 and 0.98 pu, respectively. By adjusting the SVC device properly, the load voltage was increased to the setting value.

Table II is explained as follows: The minimum voltages for the CC-PID, LC-SVC, CC-SVC, PI-SVC, PD-SVC and proposed controller were achieved at the values of 0.9660, 0.9659, 0.9664, 0.9659 and 0.9660 pu, respectively. Meanwhile, the settling times for the CC-PID, LC-SVC, CC-SVC, PI-SVC, PD-SVC and proposed controller were obtained at 6.37, 14.53, 11.57, 12.19 and 5.52 s, respectively. All controllers were able to control of voltage collapse in power systems. Moreover, a better response was given by the proposed controller than the others because the shortest settling time of load voltage temporal response was achieved by the proposed controller. It means that the load voltage of the proposed controller was faster to achieve steady state condition than the others. Control signal of the respective controllers were fed to load bus (Fig. 6).

The main function of SVC was to control and maintain reactive power in power system networks. When power systems under heavy loading and the voltage was too low, reactive power was supplied by the SVC to the networks. On the contrary, when power systems operated under light loading and the voltage tended too at high value, the reactive power was absorbed by the SVC device from the networks. In this simulation, power systems were operated under critical loading condition and SVC device was applied to power systems. The load voltage was increased to the setting value. The load voltage before SVC device applied to power systems was at the value of 0.9682 pu. On the other hand, the load voltage increased to the setting value after the SVC was applied to the systems. The difference of voltage before and after SVC applied to the systems was defined as the load voltage increased (ΔV). The load voltages increased for the LC-SVC, PI-SVC, PD-SVC and proposed controller were at the values of 0.0119, 0.0119, 0.0118 and 0.0118 pu, respectively.

Meanwhile, SVC susceptance values for the LC-SVC, PI-SVC, PD-SVC and proposed controller were obtained at the same value ($B_{SVC} = j0.0224$ pu). Fig. 7 shows temporal responses of SVC susceptance values. Firstly, the SVC susceptance values were zero, at time of 0.65 s their values sharply increased to peak overshoot at $j0.0233$ pu; then their values were decreased and damped to steady state at the values of $j0.0224$ pu. Moreover, reactive powers supplied by the SVC to power system networks for the LC-SVC, PI-SVC, PD-SVC and proposed controller were obtained at the same value ($Q_{SVC} = j0.0215$ pu). Furthermore, the load voltages for the LC-SVC, PI-SVC, PD-SVC and proposed controller were obtained at the values of 0.9801, 0.9801, 0.98 and 0.98 pu,

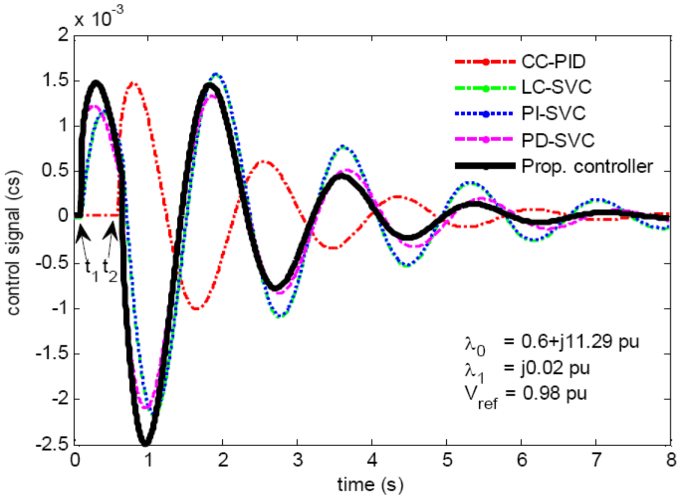

Fig. 6. Control signal of respective controllers

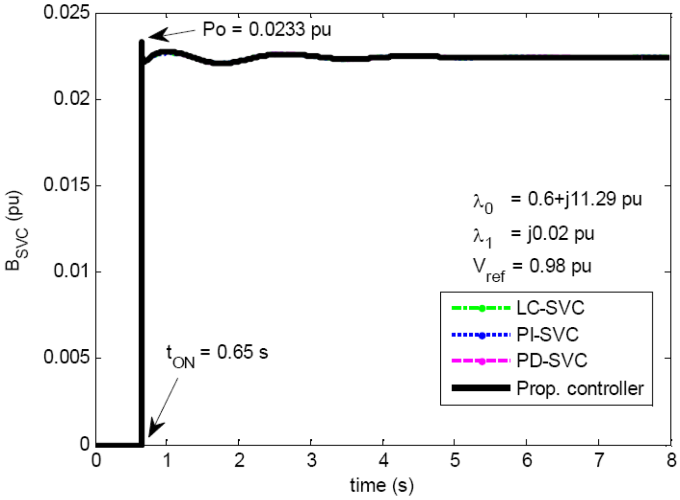

Fig. 7. Temporal responses of SVC susceptances

respectively.

The voltage collapse is able to be controlled and suppressed by all the controllers. Moreover, the proposed controller gives better performance than the other controllers. For instance, the load voltage dynamic is significantly improved using ANFIS-based CC-SVC with an additional PID-loop, indicated by the settling time decrease to the value of 5.52 s.

V. CONCLUSION

Load demand in a modern power system has grown up rapidly in recent year. Meanwhile, the increment of power plants and transmission lines being built are very slow due to economical and environmental reasons. This situation will make the systems operate in critical mode at the boundary of stability. Power systems operate in critical load cause load bus voltage value undergo to low voltage. Consequently, voltage collapse phenomenon and black out problem will occur when load bus voltage operates in very low voltage. To solve the both problems, the ANFIS-based Composite Controller (ANFIS-based CC-SVC) was proposed in this research. The ANFIS-based was chosen because its computation complexity was more efficient than Mamdani fuzzy logic controller. Three-bus power systems with an additional reactive load at the value of $j0.02$ pu were used to examine the effectiveness of proposed controller. The proposed controller was able to control of voltage collapse and to maintain the load voltage at the setting value of 0.98 pu. The settling time and increasing of load voltage were achieved at time of 5.52 s and value of 0.0118 pu, respectively.

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