Dynamic Stability Enhancement of Power Systems Using Neural-Network Controlled Static-Compensator

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Abstrak

Makalah ini bertujuan untuk peningkatan stabilitas dinamis sistem tenaga menggunakan jaringan syaraf tiruan (JST) yang dikendalikan kompensator VAR statis (SVC). SVC terbukti dapat meningkatkan stabilitas dinamis sistem tenaga. Selain sebagai kompensasi daya reaktif, SVC memiliki peran ganda dalam pengoperasian sistem tenaga. Sinyal-sinyal kontrol tambahan untuk SVC memainkan peran penting dalam mitigasi osilasi frekuensi rendah elektro-mekanis rotor. Pengendali berbasis JST yang dirancang menggunakan deviasi kecepatan generator diusulkan dalam makalah sebagai sinyal termodulasi ke SVC, untuk menghasilkan redaman yang diinginkan. JST dilatih menggunakan data pengendali konvensional dan sehingga menggantikan pengendali konvensional tersebut. SVC terkendali JST digunakan untuk meningkatkan unjuk kerja dinamis sistem tenaga dengan mengurangi galat keadaan tunak dan untuk kestabilannya secara cepat. Untuk memperoleh simpulan, simulasi dilakukan pada sistem tenaga mesin jamak (MMPS) pada berbagai kondisi operasi.

Kata kunci: FACTS, jaringan syaraf tiruan, kompensator VAR statis, sistem tenaga, stabilitas dinamis

Abstract

This paper aims at enhancement of dynamic stability of power systems using artificial neural network (ANN) controlled static VAR compensator (SVC). SVC is proven the fact that it improves the dynamic stability of power systems apart from reactive power compensation; it has multiple roles in the operation of power systems. The auxiliary control signals to SVC play a very important role in mitigating the rotor electro-mechanical low frequency oscillations. Artificial neural network based controller is designed using the generator speed deviation, as a modulated signal to SVC, to generate the desired damping, is proposed in this paper. The ANN is trained using conventional controlled data and hence replaces the conventional controller. The ANN controlled SVC is used to improve the dynamic performance of power system by reducing the steady-state error and for its fast settling. The simulations are carried out for multi-machine power system (MMPS) at different operating conditions.

Key words: artificial neural network, dynamic stability, FACTS, power system, static VAR compensator

1. Introduction

The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. Power is generated by synchronous generators that operate in synchronism with the rest of the system. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence. Thus the power system stability can be defined as the ability of the power system to return to steady state without losing synchronism. Usually power system stability is categorized into steady state, transient and dynamic stability [1], [2].

The dynamic stability (also known as small-signal stability) is the ability of a power system to maintain stability under continuous small disturbances. These small disturbances occur due to random fluctuations in loads and generation levels. In an interconnected power system, these random variations can lead catastrophic failure. The disturbances are considered sufficiently small for linearization of system equations to be permissible. The instability of power system may lead to the steady increment in rotor angle due to lack of sufficient synchronizing torque and increasing amplitude of rotor oscillations due to lack of sufficient damping torque.

The nature of system response to small disturbances depends on a number of factors including initial operating conditions, transmission system and the type of generator excitation

controls used. In today's practical power system, dynamic stability is largely a problem of insufficient damping of oscillations.

Modern Power Systems are equipped with fast acting static excitation systems, as these units become a large percentage of the generating capacity; they have a large impact upon the dynamic stability of power systems. They introduce negative damping at the electro-mechanical oscillation frequencies of the machines in the range of 0.1Hz to 2.5 Hz. They make the system unstable under local and inter-area modes of oscillations. Particularly when the system is weak and with weak tie lines even a small disturbance will make the system unstable. The purpose of dynamic stability is to examine the dynamic performance of a synchronous machine under small perturbations. Since the machine must remain in synchronism under small perturbations, it is essential to have positive damping for the machine. The damping torque of the synchronous machine is affected by a number of factors viz. machine loading, excitation controls, Power System Stabilizer parameters and loads etc. Hence, a detail-linearized model is required to examine the dynamic stability. Power System Stabilizers were developed to damp out these oscillations by modulating generator excitation and introducing positive damping to the system.

Many efforts are made to replace the conventional power system stabilizers with Fuzzy Logic Based, Flexible AC Transmission Systems (FACTS) based and Artificial Neural Network based stabilizers are proposed in the literature. This is because of the fact that the above novel approaches are superior to algorithmic methods and are adaptive in nature. They also possess fast response with reduced transients and can also adapt themselves to the non-linearity in the system. The limitation of the fuzzy based and adaptive fuzzy based stabilizers is in the development of rule base. This rule base may vary from system to system. The limitations of ANN based stabilizers are in its learning ability and suitable learning algorithms are required and this may even system dependent. Many simulated studies are made in this direction and good results are obtained [3] to [8], [11] and [12].

Flexible AC Transmission Systems (FACTS) are new devices emanating from recent innovative technologies that are capable of altering voltage, phase angle and/or impedance at particular points in power systems. Their fast response offers a high potential for power system stability enhancement apart from steady-state flow control. The simulated studies of FACTS devices reveal the fact that they improve the dynamic stability of power system if utilized properly.

Static Var Compensator (SVC) provides fast acting dynamic reactive compensation for voltage support during contingency events which would otherwise depress the voltage for a significant length of time. The SVCs with auxiliary control signals in their voltage control loops can effectively enhance the damping of power system oscillations and improve power systems stability. In last few years, many researchers have proposed techniques for tuning SVC stabilizers to improve the damping of electro-mechanical oscillations of power systems and detailed simulations of SVC have taken place to overcome the problem of dynamic stability.

This paper attempts to replace the existing conventional power system stabilizers with ANN based damping controlled SVC in order to achieve better dynamic performance. The method is tested on MMPS.

2. Mathematical Modelling
The linearized mathematical modeling of the multi-machine power system is carried out by linearizing the equations around the operating point and hence obtained the required state equations [9]. A three-machine nine-bus system is taken for the linearized modeling of multi-machine power system and hence its state equations are obtained. The order of multi-machine power system (three-machine nine-bus system) is eleventh order without power system stabilizers.

2.1. Modeling of multi-machine power system
Modeling of multi-machine power system is obtained by considering the three-machine nine-bus system. Generator1 is taken as reference and hence is modeled as classical model, Generators 2 and 3 are modeled as two-axis models. The excitation system on machines 2 and 3 are modeled as one time lag transfer function. The rotor dynamics of machines 2 and 3 are studied with respect to machine 1 [11].

Thus the state equation of the form $\dot{X} = AX + BU$ and $Y = CX + DU$ are obtained for the three machine nine bus system. The state vector X and the input vector U are as follows:

$$X^T = [\Delta\omega_1, \Delta E'_{q2}, \Delta E'_{d2}, \Delta\omega_2, \Delta E'_{q3}, \Delta E'_{d3}, \Delta\omega_3, \Delta\delta_{12}, \Delta\delta_{13}, \Delta E_{FD2}, \Delta E_{FD3}]$$

and $U^T = [\Delta T_{m1}, \Delta T_{m2}, \Delta V_{ref4}, \Delta T_{m3}, \Delta V_{ref5}]$.

Perturbations on change in d-axis stator voltages are negligible. So, eliminating $\Delta E'_{d2}$ and $\Delta E'_{d3}$ and rearranging the state equation, the Unified Philips Heffron model for the multi-machine power system is obtained and the new state vector X and the input vector U are as follows:

$$X^T = [\Delta\omega_1, \Delta E'_{q2}, \Delta\omega_2, \Delta E'_{q3}, \Delta\omega_3, \Delta\delta_{12}, \Delta\delta_{13}, \Delta E_{FD2}, \Delta E_{FD3}] \text{ and } U^T = [\Delta T_{m1}, \Delta T_{m2}, \Delta V_{ref4}, \Delta T_{m3}, \Delta V_{ref5}].$$

2.2. Basic stability models of SVC

The basic stability model of SVC [10] is used for the simulations and tested for MMPS. The basic model of SVC consists of a voltage regulator block, which estimates the susceptance value from the measurement block, which measures the current through SVC controller. The Thyristor susceptance block yields the incremental change in the susceptance value when a firing angle delay is given to it. The Z_{th} is the thevinins impedance of SVC controller, which is generally specified as a constant.

SVC with the additional PID damping controller [11] introduces an additional damping in the system and damps the rotor mechanical low frequency oscillations quickly. They are placed in the supplementary control signal of SVC. Additional PID damping controllers are used to obtain ΔV_{ref3} signal from the generator speed deviation$\Delta\omega$.

SVC with the additional ANN damping controller shown in Figure 1 is used, as this introduces an additional damping in the system and damps the rotor mechanical low frequency oscillations effectively. These ANN generated damping signals are replaced with the auxiliary conventional controlled (PID) signal of SVC, inorder to obtain a better dynamic response than without damping controller case.
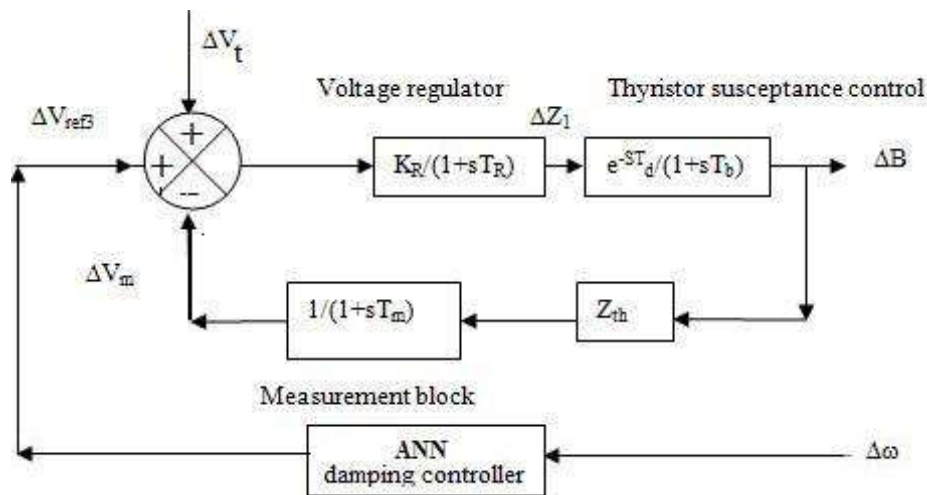
Figure 1. Dynamic modeling of SVC with additional ANN damping controller introduced in the auxiliary signals.

2.3. SVC with Neural Network damping controller

The input data $\Delta\omega_2$ and $\Delta\dot{\omega}_2$ and output data ΔV_{ref3} of conventional (PID) damping controller for SVC is used to train the ANN and hence the trained ANN is replaced with the conventional damping controller. Unified Philips Heffron model equipped with ANN damping controlled SVC is developed as shown in Figure 2.

A Feed Forward Neural Network is considered which contains 3 layers. The input layer contains two neurons and performs only summation of inputs multiplied by their respective weights. The hidden layer contains 5 neurons with the tansigmoidal activation function. The output layer contains only one neuron with the same activation function.

The training is performed with the Levenberg-Marquardt training function and learning is performed with Gradient descent with momentum weight and bias learning function. Performance is measured according to the specified mean square error performance function. The number of iterations is 416, time is 35 seconds and the gradient is 2.31e-08.

Figure 2. Philips Heffron model of MMPS with ANN damping controlled SVC

3. Results and Analysis

The MMPS (WSCC 3 machine nine-bus system) is modelled as a Philips Heffron model with ANN damping controlled SVC as shown in Figure 2. The Philips Heffron model is simulated in Matlab Simulink environment for different operating conditions and case studies like without SVC, with SVC, with PID damping controlled SVC and with ANN damping controlled SVC.

Different operating conditions are as follows:
   (i)   Operating condition 1: ΔTm_1=10%, ΔTm_2=0, ΔTm_3=0
   (ii) Operating condition 2: ΔTm_1=0, ΔTm_2=10% , ΔTm_3=0
   (iii) Operating condition 3: ΔTm_1=10%, ΔTm_2=10%, ΔTm_3=0

Different case studies are as follows:
   (i)   No SVC and No Power System Stabilizer (PSS)
   (ii) SVC on machine 2 only
   (iii) PID SVC on machine 2 only
   (iv) ANN SVC on machine 2 only

3.1. Multi-Machine Power System (MMPS)

The results of multi-machine power system for different case studies under operating condition 1, operating condition 2 and operating condition 3 are shown in Table 1, Table 2 and Table 3 respectively.

The rotor angle fluctuations on machine 2 w.r.t. machine 1 $\Delta\delta_{12}$, rotor angle fluctuations on machine 3 w.r.t. machine 1 $\Delta\delta_{13}$, terminal voltage fluctuations on machine 2 ΔV_{t2} and terminal voltage fluctuations on machine 3 ΔV_{t3}, for operating condition 1 and different case studies are shown in Figure 3.

The rotor angle fluctuations on machine 2 w.r.t. machine 1 $\Delta\delta_{12}$, rotor angle fluctuations on machine 3 w.r.t. machine 1 $\Delta\delta_{13}$, terminal voltage fluctuations on machine 2 ΔV_{t2} and terminal voltage fluctuations on machine 3 ΔV_{t3} for operating condition 2 and different case studies are shown in Figure 4.

The rotor angle fluctuations on machine 2 w.r.t. machine 1 $\Delta\delta_{12}$, rotor angle fluctuations on machine 3 w.r.t. machine 1 $\Delta\delta_{13}$, terminal voltage fluctuations on machine 2 ΔV_{t2} and terminal voltage fluctuations on machine 3 ΔV_{t3} for operating condition 3 and different case studies are shown in Figure 5.

From the results given in Table 1, Table 2 and Table 3 and responses shown Figure 1, Figure 2 and Figure 3 it is observed that the MMPS without SVC is not settling, MMPS with SVC on macnine 2 is taking large settling time.

From the results it is clear that it is very much essential that the damping controlled SVC must be placed on machine 2, to reduce the settling time of rotor oscillations and also terminal voltage fluctuations, the damping controller can be conventional PID controller or ANN controller.

The order of overall system will be reduced with ANN damping controlled SVC in comparison to PID damping controlled SVC. Hence the stability margin will be increased with ANN damping controlled SVC.

Table 1. Results of machine2 and machine3 for MMPS under operating condition 1

Case Studies	$\Delta\delta_{12}$		$\Delta\delta_{13}$		ΔV_{t2}		ΔV_{t3}	
	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec
Without SVC	0.0770	NS	0.2330	NS	-0.001032	NS	0.006900	NS
SVC on m/c2	0.0662	LST	0.2182	LST	-0.000700	LST	0.005200	LST
PID SVC on m/c2	0.0412	6	0.1072	6	-0.000514	6	0.002284	6
NN SVC on m/c2	0.0412	6	0.1072	6	-0.000511	6	0.002286	6

Table 2. Results of machine2 and machine3 for MMPS under operating condition 2

Case Studies	$\Delta\delta_{12}$		$\Delta\delta_{13}$		ΔV_{t2}		ΔV_{t3}	
	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec
Without SVC	-0.1000	NS	0.2420	NS	0.005000	NS	0.0076	NS
SVC on m/c2	-0.0700	LST	0.2820	LST	0.002500	LST	0.0079	LST
PID SVC on m/c2	-0.0375	6	0.1323	6	0.001786	6	0.0039	6
NN SVC on m/c2	-0.0375	6	0.1323	6	0.001786	6	0.0039	6

Table 3. Results of machine2 and machine3 for MMPS under operating condition 3

Case Studies	$\Delta\delta_{12}$		$\Delta\delta_{13}$		ΔV_{t2}		ΔV_{t3}	
	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec	e_{ss} in pu	t_{ss} in sec
Without SVC	0.0900	NS	0.4520	NS	0.0052	NS	0.01220	NS
SVC on m/c2	0.0625	LST	0.5000	LST	0.0016	LST	0.01300	LST
PID SVC on m/c2	0.0045	6	0.2400	6	0.0013	6	0.00630	6
NN SVC on m/c2	0.0036	6	0.2394	6	0.0012	6	0.00628	6

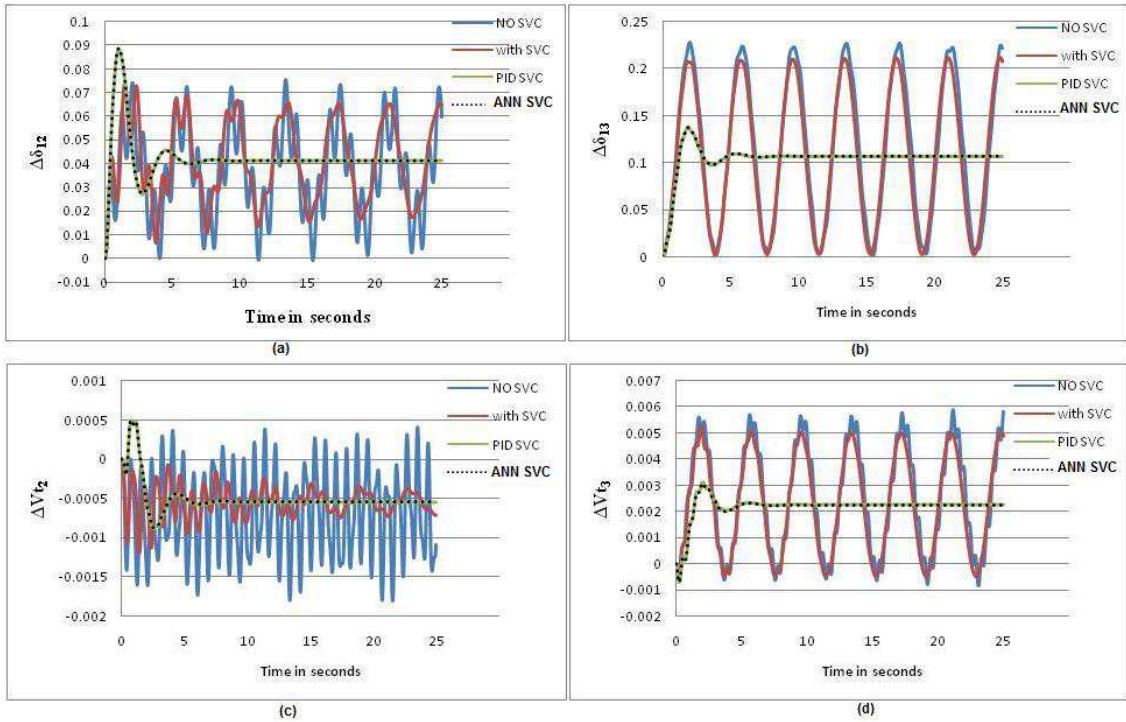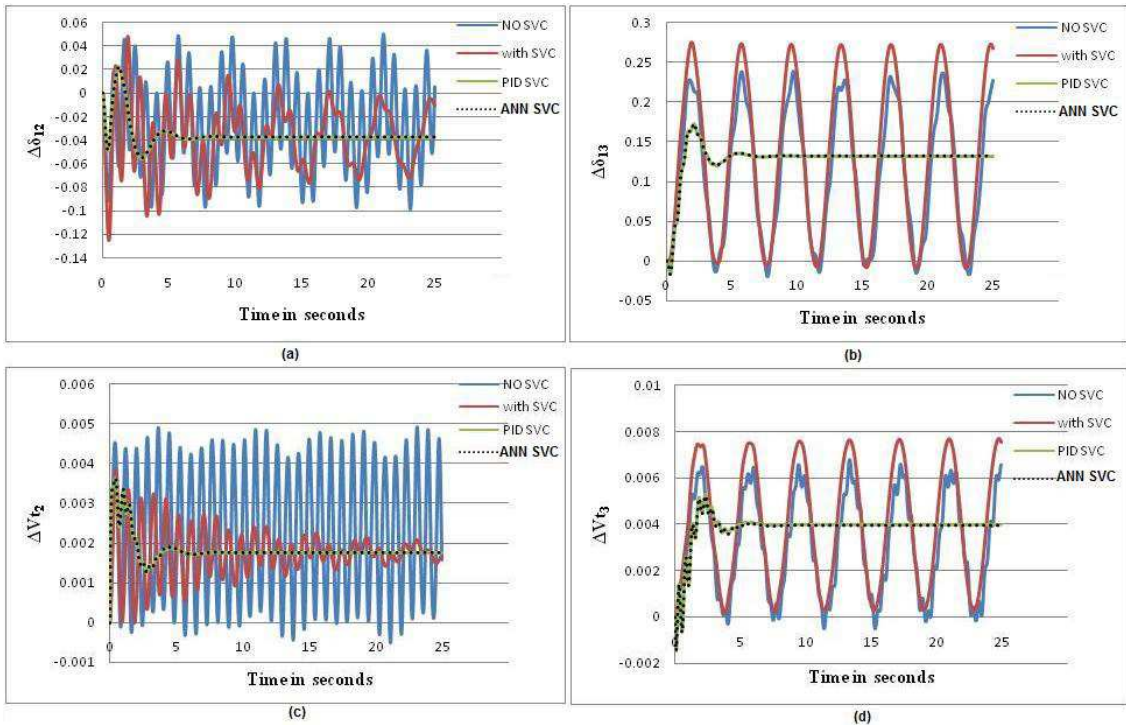NS-Not Settling, LST-Large Settling Time, e_{ss}-Steady State Error, t_{ss}-Settling time

Figure 3. (a) $\Delta\delta_{12}$ response of MMPS for operating condition 1 (b) $\Delta\delta_{13}$ response of MMPS for operating condition 1 (c) ΔVt_2 response of MMPS for operating condition 1 (d) ΔVt_3 response of MMPS for operating condition 1

Figure 4. (a) $\Delta\delta_{12}$ response of MMPS for operating condition 2 (b) $\Delta\delta_{13}$ response of MMPS for operating condition 2 (c) ΔVt_2 response of MMPS for operating condition 2 (d) ΔVt_3 response of MMPS for operating condition 2
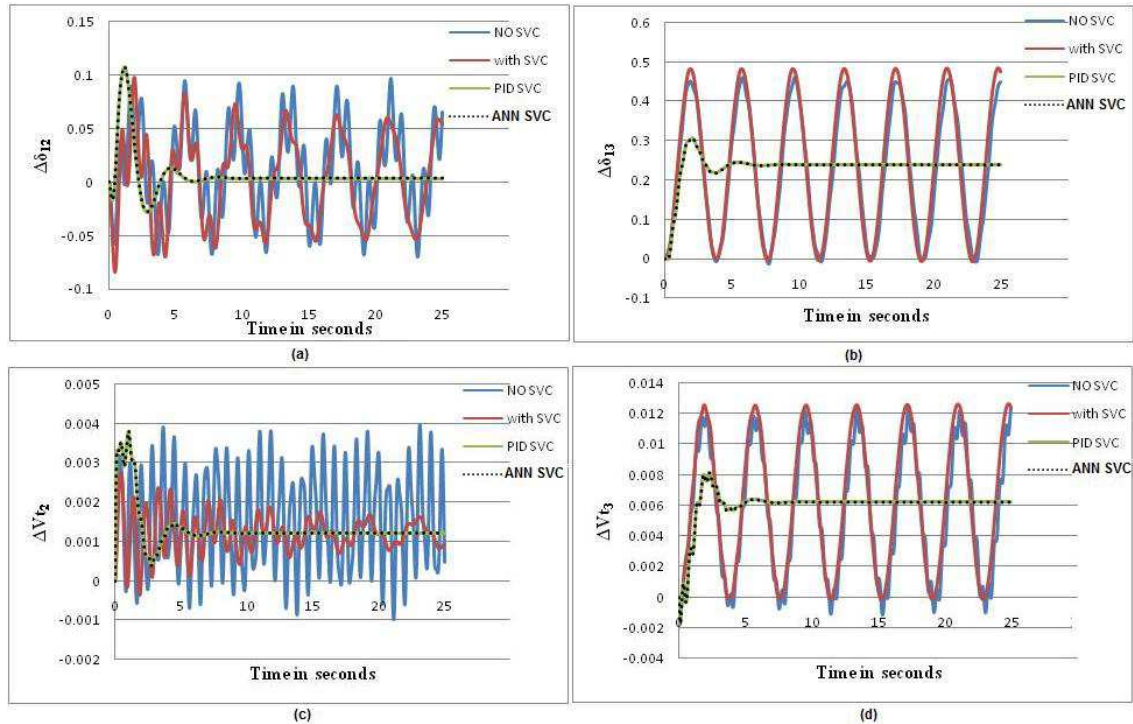
Figure 5. (a) $\Delta\delta_{12}$ response of MMPS for operating condition 3 (b) $\Delta\delta_{13}$ response of MMPS for operating condition 3 (c) ΔVt_2 response of MMPS for operating condition 3 (d) ΔVt_3 response of MMPS for operating condition 3

4. Conclusions

In this paper dynamic stability of MMPS is enhanced using ANN damping controlled SVC. Apart from damping of oscillations in the generator, terminal voltages has also been reported and tested on MMPS. The conclusions are that SVC on its own is unable to damp out the oscillations and requires an additional damping controller to improve the dynamic stability of power system. The comparison of results with SVC and proposed ANN damping controlled SVC which are tested on MMPS prove that SVC with an additional ANN damping controller can mitigate the problem of dynamic stability of power system i.e. they damp out the rotor mechanical low frequency oscillations quickly, SVC placed at the terminal bus of the machine enhances the reactive power limits of the machine and also reduces the terminal voltage fluctuations effectively. Hence, it is very clear that SVC if properly ultilized can replace the existing conventional power system stabilizers. ANN controlled SVC has an added advantage of adaptability for changing operating conditions and for the non-linearities in the system. It can also cater the needs of future expansion in power system. ANN controlled SVC hence mitigate the problem of rotor electro-mechanical low frequency oscillations intelligently. In future it can be implemented for the real-time control of power system.

Appendix

Data for 3-machine 9-bus system: (All flows are in MW and MVAR)
Generator 1 (G1): 71.6 + j27, Generator 2 (G2): 163 + j6.7 and Generator 3 (G3): 85-j10.9.
Load A: 125 + j50, Load B: 90 + j30 and Load C: 100 + j35.
Data for basic SVC stability model:
K_R = Voltage regulator Gain = 80
T_R = Voltage regulator time constant = 0.025 seconds
T_d = Thyristor susceptance control firing angle delay = 0.0371 seconds
T_b = Thyristor susceptance control time constant = 0.0375 seconds
Z_{th} = The thevenins impedance = 0.02 pu
T_m = The measurement block time constant = 0.000795 seconds

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