

SYNCHRONIZING PHASOR MEASUREMENT AND STATCOM CONTROLLER IN POWER SYSTEM STABILITY ENHANCEMENT

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Abstract: *This paper presents the concepts of Synchronizing Phasor Measurement (SPM) and its application in addition with a STATCOM controller in order to enhance dynamic stability of a multi-machine power system. The bus voltage under consideration is estimated in the form of digital signal by a Synchronizing Phasor Measurement Unit (SPMU). The DSP based output of the SPMU is then applied to a fixed structure PI type lead-lag digital STATCOM controller. The performance of this discrete-time digital controller is compared with its analog counterpart. The parameters of the analog controller are first tuned with a popular soft computation technique, Particle Swarm optimization (PSO) and later this controller is converted to digital one for simulation with DSP based outputs received from SPMU. The effectiveness of the design of the proposed control scheme is illustrated through time domain simulation of a proposed 3-machine, 9-bus test power system. The simulation results established that the Synchronizing Phasor Measurement based digital control system is more effective and resulting better performance than the continuous-time analog control system in power system stability improvement.*

Keywords: *Digital Signal Processing (DSP); Particle Swarm Optimization (PSO); Synchronizing Phasor Measurement Unit (SPMU), Static Synchronous Compensator (STATCOM).*

1. Introduction

The problem of small signal stability in power systems is a long standing issue to the researchers. Power system stabilizers (PSSs) [1] are widely used in power industries to maintain the stable operation of power systems following small and large disturbances. With ever growing changes in global economic scenario, the demand of power transfer capability and controllability of the modern power system is rising increasingly. Therefore, the uses of the modern equipments such as FACTS devices [2] are remarkably taken into account, because of its reliable, fast and economic operation. Static Synchronous Compensator (STATCOM) is an important member in the FACTS family that are

proven to be robust and effective to mitigate power system operational problems [3].

It is well established that the limitations of analog controllers can be overcome by applying Digital Signal Processing (DSP) based controllers whose operations are programmable, precise and can be easily upgraded by employing high speed, sophisticated hardware. A number of investigations on digital control schemes for power system operations and control are reported in the literature [4]-[5]. A micro-processor based design of digital controller for Static Phase Sifter (SPS) has been implemented in [6] to damp inter-area electromechanical oscillations. The concepts of DSP based measurement of voltage and current phasor are introduced in early eighties [7]. After that it is increasingly used by the researchers. In modern smart grid scenario digital signal processing based phasor measurement technology plays a key role in power system monitoring, control and protection [8]-[9].

The problem of design of any controller is the difficulties of its proper tuning. The tuning required prior knowledge of the system operating conditions. It has also had computational complexity and burden. Some global search evolutionary algorithms such as fuzzy logic control, GA based fuzzy control, Artificial Neural Network (ANN), Particle Swarm Optimization (PSO) etc. have been utilized to design and investigate many power system optimization problems [10]-[12]. Among these techniques, PSO is being increasingly used by the researchers recently [13]. PSO is robust, stable and has faster convergence properties than other optimization methods. Advantage of PSO over GA is that the 'crossover' and 'mutation' operations are not required in PSO.

In this paper the PSO based optimization method has been implemented to tune the parameters of a PI type lead-lag STATCOM controller. This controller is later converted to digital one (z-domain) via Tustin's transformation to adopt DSP based signal. The voltage phasor of local substations are considered to be measured by SPMU. The DSP

based outputs of the SPMU are then employed to the discrete-time STATCOM controller. It has also been assumed that the communication between the STATCOM controller and the SPMU are based on Global Positioning Systems (GPS) technology via wide area communication network (WAN). To the best of author's knowledge the proposed approach in this paper has not been explored detail in the existing literatures.

The content of the paper is oriented as follows: In section 2 the concepts of synchronizing phasor measurement and the Phasor Measurement Unit (PMU) has been described. The design of a PSO based conventional STATCOM damping controller in association with multimachine modelling and the configuration of digital controller have been illustrated in section 3. Finally, performance and effectiveness of the proposed DSP based control with respect to the continuous-time analog control has been investigated in section 4. Conclusion has been drawn in Section 5.

2. Synchronizing Phasor Measurement

2.1 Phasor Measurement Concepts

A phasor is a unique complex quantity, used to represent graphically a pure sinusoidal waveform. A pure sinusoidal signal can be represented by the following equation

$$X(t) = X_{max} \cos(\omega t + \phi) \quad (1)$$

The phasor of the above equation (1) can be written as

$$X(t) = \frac{X_{max}}{\sqrt{2}} e^{j\phi} \quad (2)$$

In order to measure the quantity as a bus voltage the above equation can be written as

$$V(t) = \frac{|V_{max}|}{\sqrt{2}} e^{j\phi} \quad (3)$$

A constant phasor means a stationary sinusoidal waveform but the signals under investigation are not practically constant, their frequency also variable and may contain harmonic or non-harmonic components. The task of a PMU is to extract the fundamental part and computes its phasor over a finite data set in one period of the fundamental frequency of the input signal.

The commonly employed method for estimation of phasor is to use of sampled data signal generated from the input signal, and the application of Discrete Fourier Transform (DFT) on it. If $V(n) \{ n = 0, 1, 2, \dots, N-1 \}$ are the N samples of the input signal $V(t)$ at $t = n\tau$, where τ is the sampling interval

taken over 1 period of the standard frequency of the power system, then the phasor representation is given by [14].

$$V_k = \frac{1}{\sqrt{2}} \frac{2}{N} \sum_{n=0}^{N-1} V(n) e^{-j \frac{2\pi kn}{N}} \quad \text{for } k = 0, 1, 2, \dots, N-1 \quad (4)$$

where V_k is the phasor and the sampling angle, $\theta = 2\pi/N = 2\pi f_0 \tau$ for sampling interval τ with nominal power system frequency f_0 . Note the frequency ω appear in the DFT at $\pm \omega$ can be combined, which introduces a factor 2 in front of the summation. Equation (4) is the phasor representation of the voltage input signal estimated by the DFT in one period of data window. It is worthwhile to mention that the PMU generally produces standard outputs with positive sequence phasors.

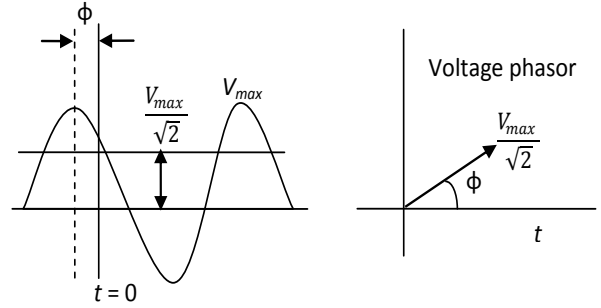


Fig. 1. Voltage signal and its phasor diagram

Assuming, $t = 0$ is the time at which the measurement is being started (Figure 1), the PMU computes the phasor as given by the equation (4) utilizing the digital data of the input signal. The equation (4) represents a non-recursive phasor measurement in a one period of fixed-length data window. It is to be noted that each time a new phasor is generated when a new sample is acquired in a data window. The continuous monitoring of this data can be handled efficiently through recursive algorithm. In recursive form the computation of phasor for each data window is done by repeating the equation (4) in identical fashion.

Let V_k represents the phasor for the sampled data set $V(n) \{ n = k, k+1, \dots, N+k-1 \}$, let a new measurement is taken to generate a new set of data $V(n) \{ n = k+1, k+2, \dots, N+k \}$. Therefore, the phasor for the new data window can be computed as

$$V_{k+1} = V_k + \frac{\sqrt{2}}{N} [V(N+k) - V(k)] e^{-jk \frac{2\pi}{N}} \quad (5)$$

It is evident that the recursive formulation (5) is simple and it involves computation of only two samples: $V(N+k)$ and $V(k)$ but in the non-recursive formulation (4) computations are

performed with N samples. A practical sampling rate around 16 times ($f_s = 16f_0$), of the standard power system frequency, $f_0 = 50\text{Hz}$ gives sampling frequency $f_s = 800\text{Hz}$, which generates $N=16$ samples in one period of the input signal. In Radix-2, Fast Fourier Transformation (FFT) algorithm requires ($N = 16 = 2^4$) 4-stages of butterfly computation. It is possible to perform this task online with the help of Digital Signal Processor (DSP) chips.

It is customary to mention that in a smart substation, all measurement signals will be time synchronized with high accuracy via Global Positioning Systems (GPS) signal. The sensing and measurement mechanisms of substation variables are assumed to be based on Synchronized Phasor Measurement technology. Therefore, it is possible to represent the phasors of all remote signals in a same phasor diagram by synchronization of their sampling process. Thus, monitoring and control of wide area signals can be possible with this technology with high fidelity from remote control centre (Figure 2).

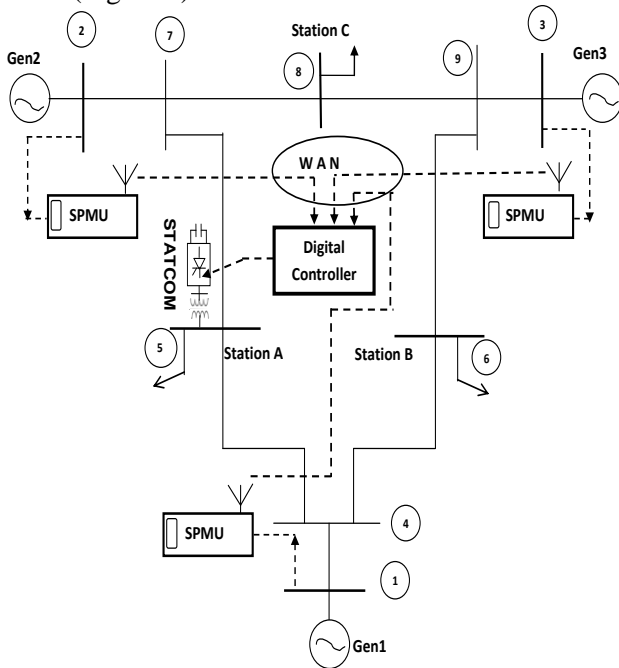


Fig. 2. Application of SPMU in wide area application

2.2 Synchronizing Phasor Measurement Unit

The block diagram of a typical Synchronizing Phasor Measurement Unit (SPMU) is shown in Figure 3. The SPMU uses time synchronizing signals from GPS system. The received GPS signals are converted to a suitable Intermediate frequency (IF) in the front end of the receiver, and then processed by microprocessor. The power station

GPS receiver is assumed to be located at point X, where three spheres with radii R_1 , R_2 , R_3 intersect (Figure 4).

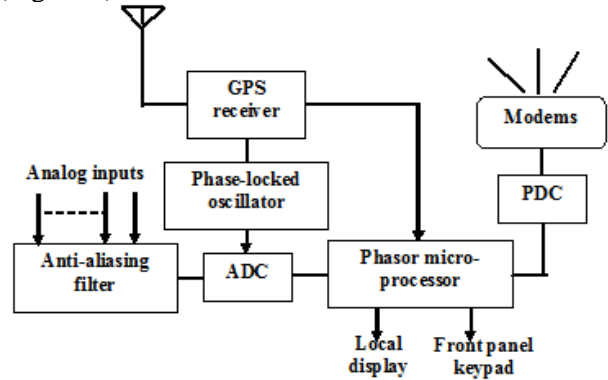


Fig. 3. Synchronizing Phasor Measurement Unit (SPMU)

The GPS receiver generates the 1 pulse-per-second (pps) signal and a time tag, which may consists of the year, day, hour, minute, and second. The 1-pps signal is converted into the required number of pulses with a phase-locked oscillator for sampling of the analog input. The microcontroller computes the positive sequence phasors using the recursive algorithm (5). The computed string of phasors, one for each of the positive sequence measurements, is assembled in a Phasor Data Concentrator (PDC) and this phasor data stream from PDC is then transmitted through a dedicated communication network at a rate of about every 2-5 cycles (40 – 100 msec) of the fundamental power system frequency (50 Hz). As the power system dynamic problems are usually initiated in the low frequency range (0.2- 2.5 Hz), therefore it is possible to study in real-time the problem of dynamic instability reliably at the control point.

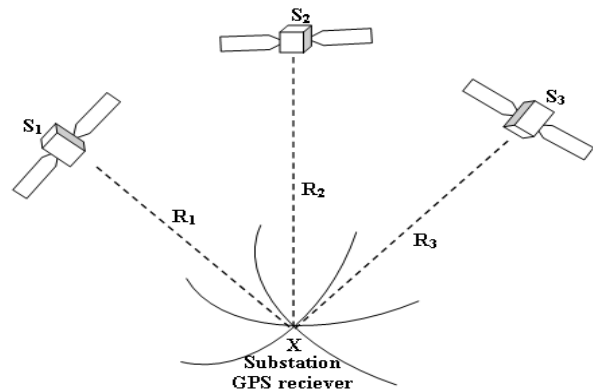


Fig. 4. Substation GPS measurement

3. Design of Analog and Digital STATCOM Controllers

3.1 Model of STATCOM Controller

The STATCOM controller model used as a voltage controller is depicted in the block-diagram (Figure 5) [15]. The STATCOM equipped with only a voltage controller is not sufficient to damp all the oscillatory modes of the system. Thus, it is usual practice to add an auxiliary control signal along with the STATCOM voltage controller. As the generator speed reflects the effect of all the oscillatory modes; therefore, the generator speed deviation is used as the auxiliary control signal for the STATCOM.

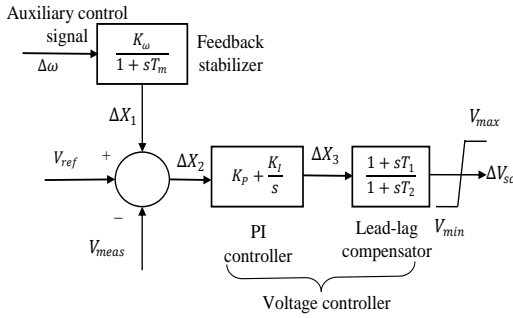


Fig. 5. STATCOM voltage controller

The block-diagram of the STATCOM voltage controller can be written with the following state-space equations;

$$\Delta \dot{X}_2 = -\frac{1}{T_m} \Delta X_2 + \frac{K_\omega}{T_m} \Delta \omega - \frac{1}{T_m} \Delta V_{meas} \quad (6)$$

$$\Delta \dot{X}_3 = \left(-\frac{K_p}{T_m} + K_i \right) \Delta X_2 + \frac{K_p K_\omega}{T_m} \Delta \omega - \frac{K_p}{T_m} \Delta V_{meas} \quad (7)$$

$$\Delta \dot{V}_{sc} = -\frac{1}{T_2} \Delta V_{sc} + \frac{1}{T_2} \Delta X_3 + \frac{T_1}{T_2} \left(-\frac{K_p}{T_m} + K_i \right) \Delta X_2 + \frac{T_1 K_p K_\omega}{T_2 T_m} \Delta \omega - \frac{T_1 K_p}{T_2 T_m} \Delta V_{meas} \quad (8)$$

3.2 Installation of STATCOM in a Multimachine System

The linearized two-axis model of a multimachine system combining basic power system components respectively exciter and power network has been described in [16]. This model can be presented with the following equations;

$$\Delta \dot{X} = A_1 \Delta X + B_1 \Delta I_g + B_2 \Delta V_g + E_1 \Delta U \quad (9)$$

$$0 = C_1 \Delta X + D_1 \Delta I_g + D_2 \Delta V_g \quad (10)$$

$$0 = C_2 \Delta X + D_3 \Delta I_g + D_4 \Delta V_g + D_5 \Delta V_l$$

$$(11)$$

$$0 = D_6 \Delta V_g + D_7 \Delta V_l \quad (12)$$

Here, (9) and (10) represent the linearized differential equations of the machine and (11) and (12) are the linearized network equations correspond to the PV buses and the PQ buses respectively. The application of an STATCOM in a multimachine system results in an addition of state variables of the STATCOM controller, $\Delta X_{Statcom} = [\Delta X_2 \ \Delta X_3 \ \Delta V_{sc}]^T$ with the machine DAE equations (9)-(10) and the power flow equations of the STATCOM in the network equations (11)-(12).

If it is assumed that the STATCOM is connected to any j -th load bus. The power flow equations of a STATCOM can be obtained as

$$P_{sc} = |V_{sc}|^2 G_{sc} - |V_{sc}| |V_j| [G_{sc} \cos(\delta_{sc} - \theta_j) + B_{sc} \sin(\delta_{sc} - \theta_j)] \quad (13)$$

$$Q_{sc} = -|V_{sc}|^2 B_{sc} - |V_{sc}| |V_j| [G_{sc} \sin(\delta_{sc} - \theta_j) - B_{sc} \cos(\delta_{sc} - \theta_j)] \quad (14)$$

where, $V_{sc} \angle \delta_{sc}$ = inverted voltage (ac) at the output of STATCOM and $Y_{sc} = G_{sc} + jB_{sc}$. All symbols have their usual significances. Therefore, linearized real power flow equations and the reactive power flow equations of the j -th load bus can be represented by the equation (15). The power flow equations for the other load buses remain unaffected.

$$\begin{bmatrix} \Delta P_j \\ \Delta Q_j \\ \Delta P_{sc} \\ \Delta Q_{sc} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_j}{\partial \theta_j} & \frac{\partial P_j}{\partial V_j} & \frac{\partial P_j}{\partial \delta_{sc}} & \frac{\partial P_j}{\partial V_{sc}} \\ \frac{\partial Q_j}{\partial \theta_j} & \frac{\partial Q_j}{\partial V_j} & \frac{\partial Q_j}{\partial \delta_{sc}} & \frac{\partial Q_j}{\partial V_{sc}} \\ \frac{\partial P_{sc}}{\partial \theta_j} & \frac{\partial P_{sc}}{\partial V_j} & \frac{\partial P_{sc}}{\partial \delta_{sc}} & \frac{\partial P_{sc}}{\partial V_{sc}} \\ \frac{\partial Q_{sc}}{\partial \theta_j} & \frac{\partial Q_{sc}}{\partial V_j} & \frac{\partial Q_{sc}}{\partial \delta_{sc}} & \frac{\partial Q_{sc}}{\partial V_{sc}} \end{bmatrix} \begin{bmatrix} \Delta \theta_j \\ \Delta V_j \\ \Delta \delta_{sc} \\ \Delta V_{sc} \end{bmatrix} \quad (15)$$

The overall system matrix with STATCOM controller for an m machine system can be obtained as

$$[A_{Statcom}]_{(7m+3) \times (7m+3)} = [A'] - [B'] [D']^{-1} [C'] \quad (16)$$

Dimensions and elements of the matrices will be modified accordingly with the addition of the state variables corresponding to the STATCOM controller. In the following section this model has been used for computation of swing modes and identification of critical swing mode in the PSO based optimization method.

It is evident from the Figure 5 that the controller can be designed with four tuning parameters; the PI controller gains (K_p , K_i), lead-lag block time

constants (T_1 , T_2). The feedback stabilizer constants K_ω and T_m are set as 5.0 and 0.5 respectively. In the following section the above unknown parameters (K_p , K_I , T_1 and T_2) of the STATCOM controllers are optimized employing PSO based technique with minimization of a desired objective function.

3.3 PSO Based Optimization Method

The Particle Swarm Optimization PSO [17] is a heuristic optimization technique inspired by the movement and intelligence of biological swarms. It is started with a population of random solutions and searches for global optima by updating generations. A ‘swarm’ consists of N particles which are assumed to be moved in a search space of dimension D . Each particle in a swarm moves following its coordinates in the search space, which are correspond to the best solution it has reached in its flight. The best particle in the population is denoted by (global best, $gbest$), while the best position that has been visited by the current particle is denoted by (local best, $pbest$). The PSO achieves optimal solution by continuous updating the velocity of each particle towards its global best and local best locations. The motion and position of the particles are evaluated by the following equations;

$$v_i(n) = \alpha * v_i(n-1) + a_1 * r_1 * (gbest_i - s_i(n-1)) + a_2 * r_2 * (pbest_i - s_i(n-1)) \quad (17)$$

$$s_i(n) = s_i(n-1) + v_i(n) \quad (18)$$

where $v_i(n)$ denotes the velocity of particle i , normally set to 10-20 % of the dynamic range of the variables. $s_i(n)$ is the position of the i th particle. a_1 , a_2 are two scalar coefficients that direct each particle towards global best and local best position respectively and their values are generally set in the range $\in (0, 2)$. r_1 and r_2 are two random variables with normal distribution in the ranges $\in (0, 1)$. α is the inertia weight of values $\in (0, 1)$.

3.4 Formulation of Optimization Problem

In this section PSO has been employed to tune the four (K_p , K_I , T_1 and T_2) unknown parameter of the STATCOM controller. The optimization problem has been solved for the minimization of a desired objective function, named as Optimum Damping Index (ODI), which is formulated by:

$$ODI = \eta = (1 - \beta_i) \quad (19)$$

where, β_i represents the damping ratio of the i -th critical swing mode of interest. The value of β and hence ‘ η ’ can be calculated from the eigenvalue analysis of the combined system matrix of the multi-machine system with STATCOM controller.

The equation (19) illustrates the facts that the maximization of the damping ratio (β) gives minimization of the desired objective function, η . Any changes in the four tuning constants of the STATCOM controller, affects the damping ratio which further changes the objective function. The possible bounds of the controller parameters can be set as follows:

Minimize η [As in (19)]

Subject to:

$$K_I^{min} \leq K_I \leq K_I^{max};$$

$$K_p^{min} \leq K_p \leq K_p^{max};$$

$$T_1^{min} \leq T_1 \leq T_1^{max}; T_2^{min} \leq T_2 \leq T_2^{max}$$

3.5 Implementation of PSO Method

In this work the PSO based optimization method has been applied through ‘PSO toolbox’ in MATLAB [18]. The ‘PSO toolbox’ consists of a main program ‘pso_Trelea_vectorized.m’ which utilizes a bunch of sub-programs to execute the optimization process. To evaluate the objective function (η), the main program follows the user defined eigenvalue computation program. The ‘particle’ has been configured with four tuning parameters of the STATCOM controller. The particle configuration can be represented by the following vector equation;

$$Particle = [K_p \ K_I \ T_1 \ T_2] \quad (20)$$

The PSO is started with a random population of each particle. The maximum and minimum value of each element in a particle has been constrained within a specified range as shown in Table 1.

Table 1 STATCOM controller parameters

Controller parameters	Typical range (Min : Max)	PSO based value	ODI (η)
K_p	(0.1 : 10.0)	8.5329	0.5679
K_I	(0.1 : 2.00)	1.0211	
T_1	(0.1 : 1.50)	0.7682	
T_2	(0.01 : 0.25)	0.0100	

The objective function ‘ η ’ corresponding to each particle has been evaluated by the user defined eigenvalue computation programme of the multimachine test system.

The PSO generates optimal values of the controller parameters which are presented in Table 1. The convergence characteristics of the objective function for the best solution with particle numbers 10 and generation 150 is shown in Figure 6. It has been observed that the convergence is guaranteed near

generation 40 and remains unchanged up to the generation limit.

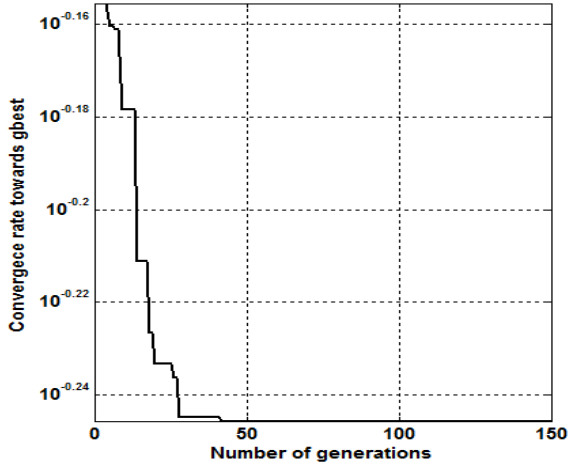


Fig. 6. Minimization rate of the desired objective function

3.6 Digital STATCOM Controller

The SPMU based voltage phasors measured from different substations are digital signal which is unable to process by the analog controller (Fig. 5). Again the direct design of higher order digital controller for a multimachine system is quite complicated. Therefore the PSO based continuous-time analog controller is converted to digital one via bi-linear (Tustin's) transformation. Hence if "s" is

substituted by the term $s = \frac{2}{\tau} \frac{1 - z^{-1}}{1 + z^{-1}}$ in the

continuous-time controller model shown in Figure 5, the resulting controller will be the digital controller. The block-diagram of the discrete-time STATCOM controller is depicted in Figure 7. The controller receives DSP based outputs, $V_{meas}(k)$ from different SPMUs installed with the generator buses. The controller generates control action signal $V_{sc}(k)$ which has to be processed further through "ZOH" before implementation to a continuous-time study power system.

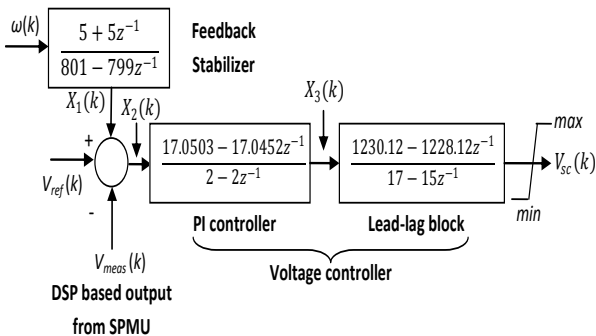


Fig. 7. Digital STATCOM controller

4. Performance Evaluation

In this section performance of both the analog and digital controllers are investigated for a step change in machine speed deviation. The step response and time-domain simulations are performed in MATLAB environment. The rotor speed deviation response of Generator #1, Generator #2 and Generator #3 are calculated and plotted in Figures 8(a), 8(b) and 8(c) respectively for a simulation time 7 sec. It has been found that performances of both the controllers are satisfactory and they are suitable for improvement of dynamic stability of the power system. Figure 8 also clearly indicating that the peak overshoots and the settling time is substantially improved with application of the digital controller compared to the case of continuous-time controller. It has been further observed that both the controllers are imparted better response in Generator # 3 compared to the response observed in Generator # 1 & Generator # 2.

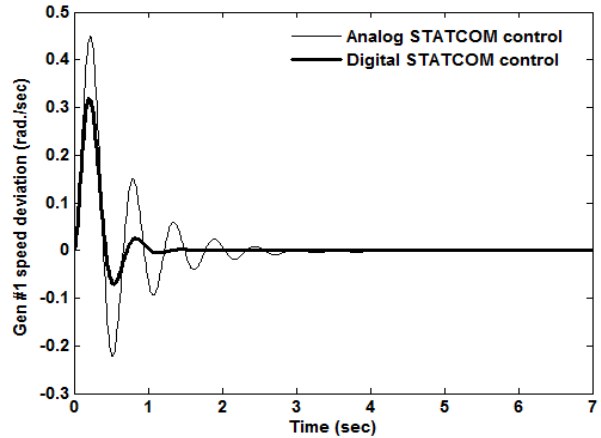


Fig. 8(a)

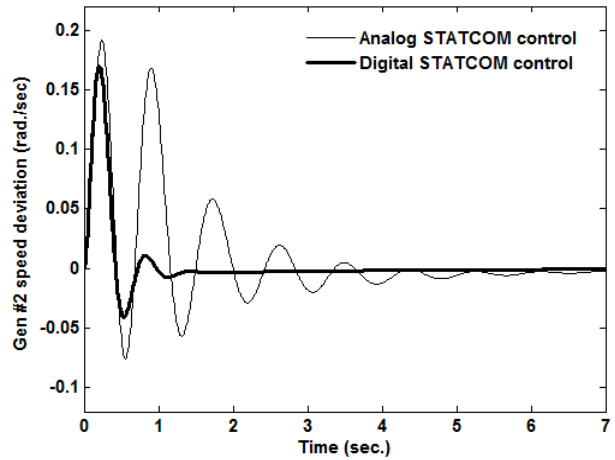


Fig. 8(b)

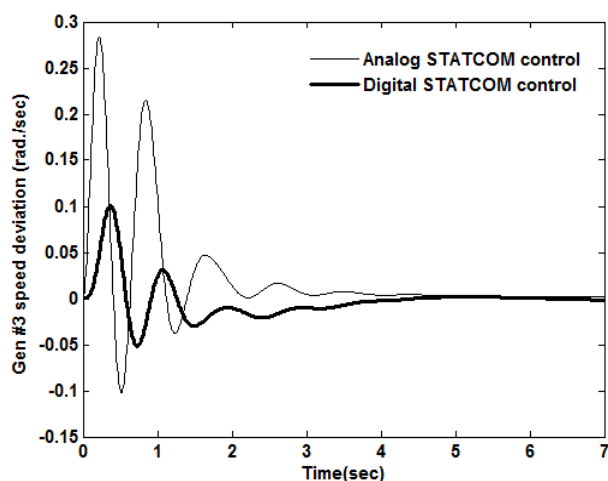


Fig. 8(c)

Fig. 8. Speed deviation response of (a) Generator #1 (b) Generator #2 (c) Generator #3

Therefore, from the simulation results presented in Figure 8, it is possible to conclude that the digital STATCOM controller is more effective in respect to the continuous-time analog controller in mitigating dynamic instability problems in a power system.

5. Conclusions

In this paper the concept of synchronizing phasor measurement and its utilization in enhancing power system stability has been described. A PI type lead-lag STATCOM controller along with SPMU is employed to investigate the dynamic stability problem of a multimachine power system. The parameters of the STATCOM controller is optimized by the PSO based optimization method via minimization of an objective function. The PSO based controller is converted to digital one via Tustin's transformation for the purpose of analysis. The performance of both the digital input based control system and the analog control system is compared. It has been established that the digital control system is more effective and superior than analog control system. The relevancy of application of SPMU is that it is possible to install digital control in the power system and also its implementation in Wide Area Control (WAC) in a multi area power system. It is to be noted that the limitation of the wide area control like signal latency or transmission delay is not considered here. The present work can be extended further considering signal transmission delay. The proposed approach can also be implemented for other FACTS controller in any multimachine power system.

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