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Power Oscillation Damping Controller Using STATCOM with Energy Storage

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ABSTRACT: Power system oscillations occur in power networks as a result of contingencies such as faults or sudden changes in load or generation. These oscillations do not usually damp out in tie-lines unless certain controls are applied to the system. This paper deals with a FUZZY based poweroscillation damping (POD) controller for a static synchronouscompensator (STATCOM)equipped with energy storage. In the fuzzy logic technique we used modifiedrecursive least square (RLS) algorithm. It is an accurate technique to damping low frequency electromechanical oscillations in the power system. When fault occurred E-STATCOM will activate and injects active and reactive power into two-machine model power systemnetwork to control the oscillations. The entire project strategy is verified through simulation results.

KEYWORDS: recursive least square (RLS), staticsynchronous compensator (STATCOM), Energy storage, Fuzzy Control, low-frequency oscillation, poweroscillation damping (POD), two-machine system model.

I. INTRODUCTION

Flexible ac transmission systems (FACTS)[1] device like static synchronous Compensator (STATCOM) applications [2] are increasing in power systems. This is due to their ability to stabilize the transmission systems [3][4] and to improve power quality in distribution systems. STATCOM is popularly accepted as a reliable reactive power controller. This device provides reactive power compensation, active power oscillation damping, flicker attenuation, voltage regulation, etc.

Generally, in high-power applications, var compensation is achieved using multilevel inverters. These inverters consist of a large number of dc sources which are usually realized by capacitors. But, due to mismatch in conduction and switching losses of the switching devices, the capacitors voltages are unbalanced. Balancing these voltages is a major research challenge in multilevel inverters. Static synchronous compensator (STATCOM) is a key device for reinforcement of the stability in an ac power system. This device has been applied both at distribution level to mitigate power quality phenomena and at transmission level for voltage control and power oscillation damping (POD) [5].Although typically used for reactive power injection only, by equipping the STATCOM with an energy storage connected to the dc-link of the converter, a more flexible control of the transmission system [1]can be achieved.

Low-frequency electromechanical oscillations[6] (typically in the range of 0.2 to 2 Hz) are common in the power system and are a cause for concern regarding secure system operation, especially in a weak transmission system.

The control of STATCOM with energy storage (named hereafter as E-STATCOM)[7][8] for power system stability enhancement has been discussed in the literature[3]. However, the impact of the location of the E-STATCOM on its dynamic performance is typically not treated. When active power injection is used for POD, the location of the E-STATCOM has a significant impact on its dynamic performance. Moreover, the typical control strategy of the device for POD available in the literature is similar to the one utilized for power system stabilizer (PSS), where a series of wash-out and lead-lag filter links are used to generate the control input signals. This kind of control strategy is effective only at the operating point where the design of the filter links is optimized, and its speed of response is limited by the frequency of the electromechanical oscillations.In this paper, a control strategy for the E-STATCOM when used for POD will be investigated.

The control strategy optimizes the injection of active and reactive power [9] to provide uniform damping at various locations in the power system. It will be shown that the implemented control algorithm is robust against system

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parameter uncertainties. For this, a modified recursive least square (RLS) [10] based estimation algorithm as described in will be used to extract the required control

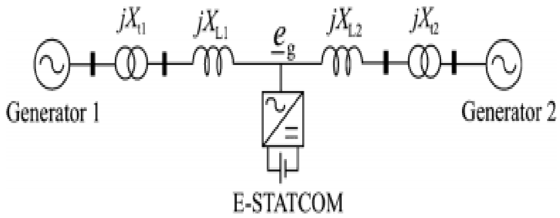

Fig.1. Simplified two-machine system with E-STATCOM.

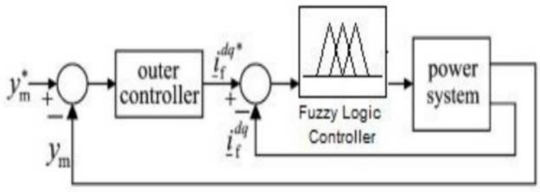

Fig. 2. Block diagram of Fuzzy control for E-STATCOM.

Signals from locally measured signals. Finally, the effectiveness of the proposed control strategy will be verified via simulation

FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, interference engine and defuzzification.

The FC is characterized as; i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani"s „min" operator. v. Defuzzification using the „height" method.

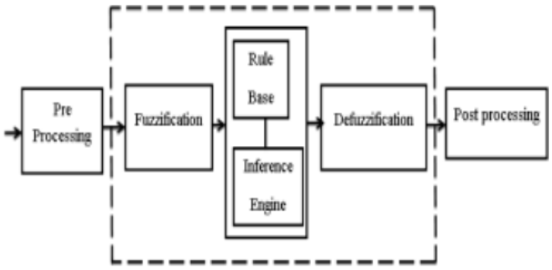

Fig.3 Fuzzy Logic Controller

II. SYSTEM MODELING FOR CONTROLLER DESIGN

A simplified power system model, such as the one depicted in Fig. 1, is used to study the impact of the E-STATCOM on the power system dynamics. The investigated system approximates an aggregate model of a two-area power system, where each area is represented by a synchronous generator.

The synchronous generators are modeled as voltage sources of constant magnitude(V_{g1}, V_{g2}) and dynamic rotor angles$(\delta_{g1}, \delta_{g2})$behind a transient reactance (X'_{d1}, X'_{d2}).The transmission system consists of two transformers represented by their equivalent leakage reactance(X_{t1}, X_{t2}) and a transmission line with equivalent reactance

($X_L = X_{L1} + X_{L2}$). The losses in the transmission system are neglected for simpler analytical expressions. If the mechanical damping in the generators is neglected, the overall damping for the investigated system is equal to zero. Therefore, the model is appropriate to allow a conservative approach of the impact of the E-STATCOM when used for stability studies. For analysis purpose, the electrical connection point of the converter along the transmission line is expressed by the parameter *a*as

$$a = \frac{X_1}{(X_1 + X_2)} \quad (1)$$

Where

$$X_1 = X'_{d1} + X_{t1} + X_{L1}$$
$$X_2 = X'_{d2} + X_{t2} + X_{L2}.$$

The control of the E-STATCOM consists of an outer control loop and an inner current control loop, as shown in Fig. 2. The outer control loop, which can be an ac voltage, dc-link voltage or POD controller, sets the reference current for the inner current controller. The generic measured signal y_m depends on the type of outer loop control. The control algorithm is implemented in -reference frame where a phase-locked loop (PLL) [11] is used to track the grid-voltage angle θ_g from the grid-voltage vector. By synchronizing the PLL with the grid-voltage vector, the - and -components of the injected current (i_f^d and i_f^q) control the injected active and reactive power,

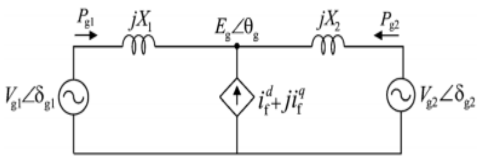

Fig. 4.Equivalent circuit for two-machine system with E-STATCOM.

respectively. In the notation in Fig. 2, the superscript "* " denotes the corresponding reference signals.
In this paper, the outer control loop is assumed to be a POD controller, and the detail of the block will be described in Section III. For this reason, we assume that the injected active and reactive powers in the steady state are zero. When designing a cascaded controller, the speed of outer control loop is typically selected to be much slower than the inner one to guarantee stability. This means that the current controller can be considered infinitely fast when designing the parameters of the outer controller loop.
The level of power oscillation damping provided by the converter depends on how much the active power output from the generators is modulated by the injected current, . For the system in Fig. 3, the change in active power output from the generators due to injected active and reactive power from the E-STATCOM is calculated as in

$$\Delta P_{g1,P} \approx -\Gamma_P P_{inj}, \quad \Delta P_{g2,P} \approx -(1-\Gamma_P)P_{inj}$$
$$\Delta P_{g1,Q} \approx \left[\frac{V_{g1}V_{g2}\sin(\delta_{g10}-\delta_{g20})a(1-a)}{E_{g0}^2}\right]Q_{inj}$$
$$\Delta P_{g2,Q} \approx -\left[\frac{V_{g1}V_{g2}\sin(\delta_{g10}-\delta_{g20})a(1-a)}{E_{g0}^2}\right]Q_{inj} \quad (2)$$

Where ($\Delta P_{g1,P}, \Delta P_{g2,P}$) and ($\Delta P_{g1,Q}, \Delta P_{g2,Q}$) represent the change in active power from the corresponding generators due to injected active power (P_{inj}) and reactive power (Q_{inj}), respectively. Γ_P, P_{inj}, and Q_{inj} are given by

$$\Gamma_P = \frac{\left([(1-a)V_{g1}]^2 + a(1-a)V_{g1}V_{g2}\cos(\delta_{g10}-\delta_{g20})\right)}{E_{g0}^2}$$
$$P_{inj} \approx E_{g0} i_f^d$$
$$Q_{inj} \approx -E_{g0} i_f^q. \quad (3)$$

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The initial steady-state PCC voltage magnitude E_{go} and generator rotor angles$(\delta_{g10}, \delta_{g20})$ correspond to the operating point where the converter is in idle mode.

It can be seen from (2) and (3) that the change in active power output from the generators depends on the location of the converter as well as on the amount of injected active and reactive power. Moreover, it can be understood from (2) that the effect of reactive power injection depends on the magnitude and direction of transmitted power from the generators.

III. POD CONTROLLER DESIGN

The derivation of the POD controller from locally measured signals will be made in this section.

A. DERIVATION OF CONTROL INPUT SIGNALS

Considering the simplified two-machine system in Fig. 1, the active power output from each generator should change in proportion to the change in its speed to provide damping. From (2), it can be observed that the effect of the power injected by the compensator on the generator active power output highly depends on the parameter, i.e., on the location of the E-STATCOM. Using the equivalent system in Fig. 3, a control input signal that contains information on the speed variation of the generators can be derived. When the E-STATCOM is not injecting any current, the variation of the locally measured signals, and at different E-STATCOM connection points using the dynamic generator rotor anglesδ_{g1} *and* $\delta_{g2}$is given by

$$\theta_g = \delta_{g2} + \tan^{-1}\left[\frac{(1-a)V_{g1}\sin(\delta_{g1}-\delta_{g2})}{(1-a)V_{g1}\cos(\delta_{g1}-\delta_{g2})+aV_{g2}}\right] \quad (4)$$

$$P_{\text{tran}} = \frac{V_{g1}V_{g2}\sin(\delta_{g1}-\delta_{g2})}{X_1+X_2}. \quad (5)$$

From a small-signal point of view and under the assumption that the PCC-voltage magnitude along the line does not change significantly, the required control input signals can be derived from the PCC-voltage phase and transmitted active power as

$$\frac{d\theta_g}{dt} \approx \Gamma_P\omega_{g0}\Delta\omega_{g1} + (1-\Gamma_P)\omega_{g0}\Delta\omega_{g2} \quad (6)$$

$$\frac{dP_{\text{tran}}}{dt} \approx \left\{\frac{V_{g1}V_{g2}\cos(\delta_{g10}-\delta_{g20})}{X_1+X_2}\right\}\omega_{g0}[\Delta\omega_{g1}-\Delta\omega_{g2}] \quad (7)$$

Where the constant $\Gamma_p$has been defined in the previous section. The nominal system frequency is represented by ω_{go} whereas $\Delta\omega_{g1}$ and $\Delta\omega_{g2}$ represent the speed variation of the generators in p.u. The electromechanical dynamics for each generator [i=1,2] is given by

$$2H_{gi}\frac{d\Delta\omega_{gi}}{dt} = \Delta T_{mi} - \Delta T_{gi} - K_{Dmi}\Delta\omega_{gi} \quad (8)$$

Where H_{gi} , $\Delta\omega_{gi}$, ΔT_{mi}, ΔT_{gi}, and K_{Dmi} represent inertia constant, speed variation, change in input torque, change in output torque and mechanical damping constant for the ith generator, respectively.

The derivative of the PCC-voltage phase and transmitted active power are both dependent on the speed variation of the generators. Moreover, the derivative of the PCC-voltage phase depends on the location of E-STATCOM, through the parameterΓ_p ,as well as the mechanical dynamics of the generators as shown in (8). This information will be exploited in the POD controller design.

For the two machine system in Fig. 1, damping is related to the variation of the speed difference between the two generators,$\Delta\omega_{g12} = \Delta\omega_{g1} - \Delta\omega_{g2}$. From (2) and (3), it can be understood that the change in the output power from the generators due to injected active power is maximum when the compensator is installed at the generator terminals (i.e.a=0 and a=1). Assuming equal inertia constant for the two generators, no damping is provided by injection of active power at the electrical midpoint of the line (i.e.a=0.5,for$H_{g1} = H_{g2}$) as the power output of the two generators is

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the same and the net impact is zero. At this location, the derivative of PCC-voltage phase is zero.This means that $\frac{d\theta}{dt}$scales the speed variation of the two generators depending on the location of E-STATCOM and its magnitude changes in proportion to the level of damping by active power injection. Therefore $\frac{d\theta_g}{dt}$ is an appropriate input signal for controlling the active power injection. On the other hand, it can be understood from (2) that the change in the output power from the generators due to injected reactive power is maximum at the electrical midpoint of the line (i.e a=0.5) and minimum at the generator terminals (i.e a=0 and a=1).As the changes in the power output of the two generators are the same in magnitude and opposite in sign, a signal that varies linearly with the speed variation between the two generators,$\Delta\omega_{g12}$ is an appropriate signal to control reactive power injection. This information can be obtained from the derivative of the transmitted active powerdP_{tran}/dt.

B. ESTIMATION OF CONTROL INPUT SIGNALS

As described in the Introduction, effective power oscillation damping for various power system operating points and E-STATCOM locations require fast, accurate, and adaptive estimation of the critical power oscillation frequency component. This is achieved by the use of an estimation method based on a modified RLS algorithm. For reasons described in the previous subsection, the derivative of the PCC-voltage phase and the transmitted power should be estimated for controlling the active and reactive power injection, respectively. The aim of the algorithm is therefore to estimate the signal components that consist of only the low-frequency electromechanical oscillation in the measured signals θ_g andP_{tran}.By using a PLL with bandwidth much higher than the frequency of electromechanical oscillations, the derivative of the PCC-voltage phase can be obtained from the change in frequency estimate of the PLL ($\Delta\omega_g = d\theta_g/dt$). Therefore, the low-frequency electromechanical oscillation component can be extracted directly from the frequency estimate of the PLL. On the other hand, the derivative of transmitted power is estimated by extracting the low-frequency [12][13] electromechanical oscillation component from the measured signal, P_{tran} and then applying a phase shift of $\pi/2$ to the estimated oscillation frequency component.

From the estimated control input signals $\tilde{\omega}_{g,osc} = d\theta_{gosc}/dt$ and $dP_{tran,osc}/dt$ which contain only a particular oscillation frequency component, the reference injected active and reactive current components(i_f^{d*}, i_f^{q*})from the E-STATCOM can be calculated to setup the POD controller as in Fig. 5. The Fuzzy logic controller is used in place of PI controller for the active and reactive current components, respectively.

To describe the estimation algorithm, an input signal which could be either ω_g or P_{tran} as shown in Fig. 5, is considered. Following a power system disturbance, will consist of an average value that varies slowly and a number of low-frequency oscillatory components, depending on the number of modes that

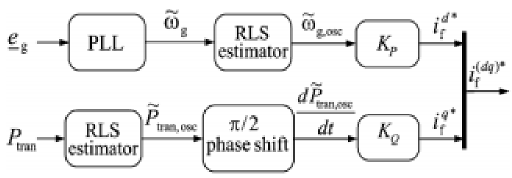

Fig. 5. Block diagram of the POD controller.

are excited by the disturbance. For simplicity, let us assume that there exists a single oscillatory component in the input signal. Therefore, the input signal consists of an average component Y_{avg} and an oscillatory componentY_{osc}which can be modeled as

$$y(t) = Y_{\text{avg}}(t) + Y_{\text{ph}}(t)\cos\left[\omega_{\text{osc}}t + \varphi(t)\right] \qquad (9)$$

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Where Y_{osc} is expressed in terms of its amplitude (Y_{ph}) frequency (ω_{osc}) and phase (φ) The model in (9) is rewritten using the oscillation angle θ_{osc}(t) =$\omega_{osc}\ t$ as

$$y(t) = Y_{\rm avg}(t) + Y_{{\rm ph},d}(t)\cos(\theta_{\rm osc}(t)) - Y_{{\rm ph},q}(t)\sin(\theta_{\rm osc}(t))$$

Where the terms $P_{ph,d}$ and $P_{ph,q}$ are given by

$$Y_{{\rm ph},d}(t) = Y_{\rm ph}(t)\cos(\varphi(t)) \quad Y_{{\rm ph},q}(t) = Y_{\rm ph}(t)\sin(\varphi(t)).$$

From an observation matrix and measured input signal y(t) , the estimated state vector is derived using the RLS algorithm in discrete time as

$$\tilde{\mathbf{h}}(k) = \tilde{\mathbf{h}}(k-1) + \mathbf{G}(k)\left[y(k) - \Phi(k)\tilde{\mathbf{h}}(k-1)\right] \qquad (10)$$

With

$$\tilde{\mathbf{h}}(k) = \left[\tilde{Y}_{\rm avg}(k) \quad \tilde{Y}_{{\rm ph},d}(k) \quad \tilde{Y}_{{\rm ph},q}(k)\right]^{\rm T}$$
$$\Phi(k) = [1 \quad \cos(\theta_{\rm osc}(k)) \quad -\sin(\theta_{\rm osc}(k))].$$

Calling I the identity matrix, the gain matrix G and covariance matrix R are calculated recursively starting with an initial invertible matrix R(0) as

$$\mathbf{G}(\mathrm{k}) = \mathbf{R}(\mathrm{k}-1)\Phi^{\rm T}(\mathrm{k})\left[\lambda + \Phi(\mathrm{k})\mathbf{R}(\mathrm{k}-1)\Phi^{\rm T}(\mathrm{k})\right]^{-1} \qquad (11)$$

$$\mathbf{R}(\mathrm{k}) = \frac{[\mathbf{I} - \mathbf{G}(\mathrm{k})\Phi(\mathrm{k})]\,\mathbf{R}(\mathrm{k}-1)}{\lambda} \qquad (12)$$

Where λ represents the forgetting factor for the RLS algorithm such that 0<$\lambda < 1$. With representing the sampling time, the steady-state bandwidth of the RLS α_{RLS} and the estimation error $\varepsilon(k)$ are given by

$$\alpha_{\rm RLS} = \frac{(1-\lambda)}{T_s}, \quad \epsilon(k) = y(k) - \Phi(k)\tilde{\mathbf{h}}(k-1).$$

Modification in the Conventional RLS Algorithm:

The selection of α_{RLS} is a tradeoff between a good selectivity for the estimator and its speed of response. A high forgetting factor results in low estimation speed with good frequency selectivity. With increasing estimation speed (decreasing λ), the

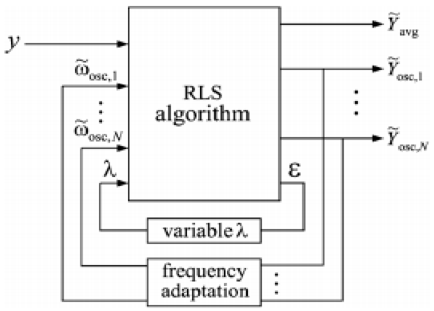

Fig. 6. Block diagram of the modified RLS estimator for multiple oscillation modes.

frequency selectivity of the algorithm reduces. For this reason, the conventional RLS algorithm must be modified in order to achieve fast transient estimation without compromising its steady-state selectivity. In this paper, this is achieved with the use of variable forgetting factor as described in. When the RLS algorithm is in steady-state, its bandwidth is determined by the steady-state forgetting factor (λ_{SS}).If a rapid change is detected in the input (i.e., if the estimation error magnitude,$|\varepsilon\ (k)|$ exceeds a predefined threshold), λ will be modified to a smaller transient forgetting

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factor (λ_{tr}).Thus, by using a high-pass filter with time constant τ_{hp} , will be slowly increased back to its steady-state value λ_{ss}) .

Therefore, a frequency adaptation mechanism as described in is implemented to track the true oscillation frequency of the input from the estimate of the oscillatory component Y_{osc}.

Modification for Multiple Oscillation Modes:

The investigated control method has been derived under the assumption of a single oscillatory frequency component in the input signal. A brief description of how the proposed algorithm can be extended for multi-area system with multiple oscillation modes will be briefly presented here for future reference. Assuming that the input signal y contains N oscillatory components, (9) must be modified as

$$y(t) = Y_{\rm avg}(t) + \sum_{i=1}^{N} Y_{{\rm osc},i}$$
$$= Y_{\rm avg}(t) + \sum_{i=1}^{N} Y_{{\rm ph},i}(t)\cos\left[\omega_{{\rm osc},i}t + \varphi_i(t)\right] \quad (13)$$

Where the ith oscillation mode Y_{osci} (with i=...N,) is expressed in terms of its amplitude ($Y_{ph,i}$), frequency ($\omega_{osc,i}$), and phase ($\emptyset_i$) Using the model in (13), the RLS described in the previous sections (including variable forgetting factor and frequency be modified as described in Fig. 6. Thus, the POD controller in Fig. 5 can be modified accordingly to control each mode independently. Observe that the phase-shift applied for calculation of the reference currents depends on the investigated system and needs to be calculated for each oscillatory mode adaptation for each considered oscillation mode.

IV. SIMULATION RESULTS

The POD controller described in Section III is here verified via MATLAB simulation using the well known two-area four-machine system in Fig. 7. The implemented system is rated 20/230 kV, 900 MVA and the parameters for the generators and transmission system together with the loading of the system are given in detail in. The system is initially operating in steadystate with a transmitted active power, 400 MW from area 1 to area 2. A three-phase fault is applied to the system on one of the transmission lines between bus 7 and bus 8.

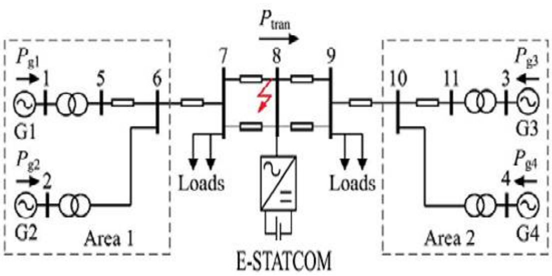

Fig. 7.Simplified two-area four machine power system.

The fault is cleared after 250ms by disconnecting the faulted line. Due to the applied disturbance, a poorly damped oscillation is obtained after the fault clearing.

After POD controller performance VSC activate and that converted voltage stored in a battery [14]. After that inverted power injected to bus. Injected power at different buses is shown in Fig. 8. As described in the small-signal analysis for two-machine system in, when moving closer to the generator units, a better damping is achieved by active power injection shows in Fig. 8(a). With respect to reactive power injection, maximum damping action is provided when the E-STATCOM is connected close to the electrical midpoint of the line and the level of damping decreases when moving away from it shows in Fig.8(d). Because of a good choice of signals for controlling both active and

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reactive power injection, effective power oscillation damping is provided by the E-STATCOM irrespective of its location in Fig. 8(b).

Due to injection of Active power we can see from Fig.8(a) wave form oscillations decreased but some spike is presented. Fig.8(b) shows signal settle down very quickly due to injection of active and reactive power. There we successfully damp out the oscillations. In Fig.8(c) wave form totally oscillated and more time taken to reach steady state position i.e. with out POD technique. By injecting reactive power also wave form comes to steady state, with out any spikes. That we can see in Fig.8(d).

All wave forms in fig.8 consist on X-axis shows power in per unit values(0.35,0.4,0.45,0.5,0.55) and Y-axis shows time(2,4,6,8,10,12) in seconds.

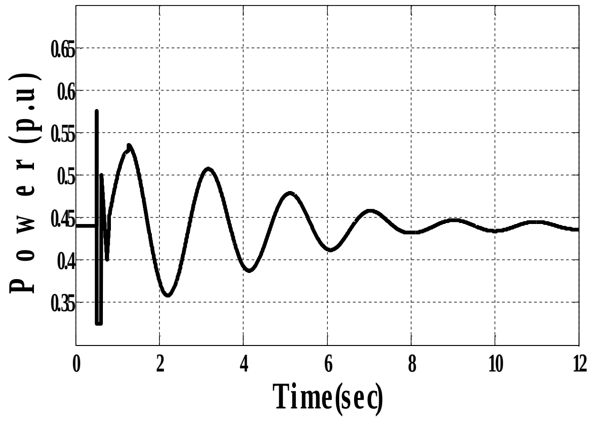

Fig.8(a) 3-phase fault with E-STATCOM connected at bus 7 (Pinj)

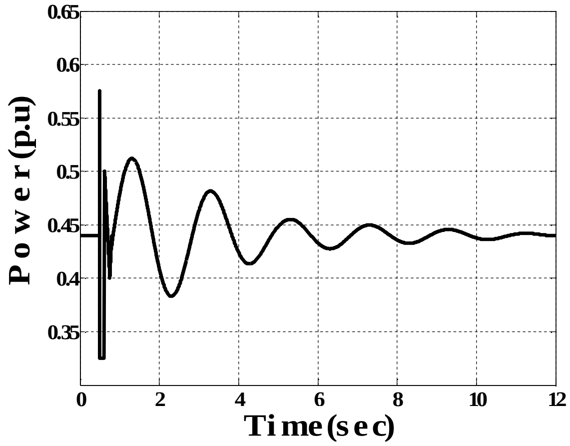

Fig.8(b) 3-phase fault with E-STATCOM connected at bus 7 (Pinj&Qinj)

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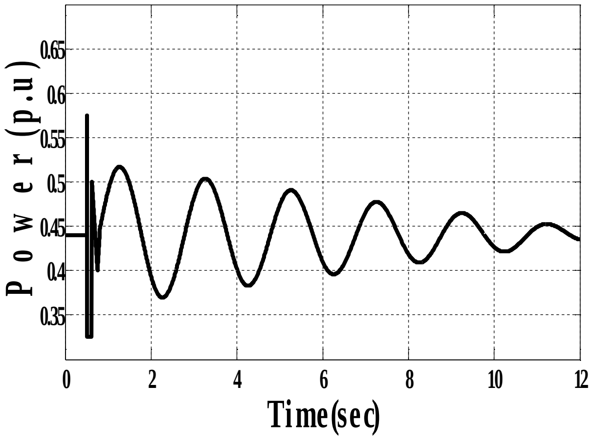

Fig.8(c) 3-phase fault with E-STATCOM connected at bus 7Without POD

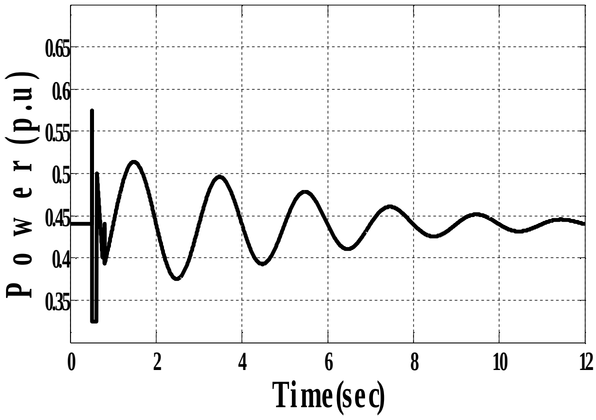

Fig.8(d) 3-phase fault with E-STATCOM connected at bus 7 (Qinj)

Fig. 8. Measured transmitted active power output following a three-phase fault with E-STATCOM.

V. CONCLUSION

An adaptive POD controller by E-STATCOM has been developed in this paper. For this, a modified RLS algorithm has been used for estimation of the low-frequency electromechanical oscillation components from locally measured signals during power system disturbances. The dynamic performance of the POD controller to provide effective damping at various connection points of the E-STATCOM has been verified through simulation verification. It also is design to enhance the power quality by controlling fluctuations, harmonic distortion. Stability and reliability of the system will increase. Reactive power compensates.

Comparison between with pod and with out pod:

With out pod wave form consists more oscillations. That is oscillated for more time. Few spikes are presented at top of wave forms.

With pod technique wave form consists negligible oscillation and wave form settled quickly in steady state period. Noise also reduced. No spikes are presented. Transient period of the wave form decreased.

The simulation results show that the power oscillations can be mitigate by inserting E-STATCOM . Power factor also increase close to unity.This results in an optimal use of the available energy source.

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