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Fuzzy Controller Based E-Statcom for Power Oscillation Damping In Power Systems

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ABSTRACT

This paper deals with the design of an adaptive power oscillation damping (POD) controller for a static synchronous compensator (STATCOM) equipped with energy storage. This is achieved using a signal estimation technique based on a modified recursive least square (RLS) algorithm, which allows a fast, selective, and adaptive estimation of the low-frequency electromechanical oscillations from locally measured signals during power system disturbances. The proposed method is effective in increasing the damping of the system at the frequencies of interest, also in the case of system parameter uncertainties and at various connection points of the compensator. First, the analysis of the impact of active and reactive power injection into the power system will be carried out using a simple two-machine system model.

A control strategy that optimizes active and reactive power injection at various connection points of the STATCOM will be derived using the simplified model. Small-signal analysis of the dynamic performance of the proposed control strategy will be carried out. The effectiveness of the proposed control method to provide power oscillation damping irrespective of the connection point of the device and in the presence of system parameter uncertainties will be verified through simulation and experimental results.

I. INTRODUCTION

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) [1][3].

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 can be achieved [4], [5]. An installation of a STATCOM with energy storage is already found in the U.K. for power flow management and voltage control [6]. The introduction of wind energy and other distributed generation will pave the way for more energy storage into the power system and auxiliary stability enhancement function is possible from the energy sources [7].

Because injection of active power is used temporarily during transient, incorporating the stability enhancement function in systems where active power injection is primarily used for other purposes [8] could be attractive. Low-frequency electromechanical oscillations (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 [9]. In this regard, FACTS controllers, both in shunt and series configuration, have been widely used to enhance stability of the power system [1]. In the specific case of shunt connected FACTS controllers [STATCOM and static var compensator (SVC)],first swing stability and POD can be achieved by modulating the voltage at the point of common coupling (PCC) using reactive power injection. However, one drawback of the shunt

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configuration for this kind of applications is that the PCC voltage must be regulated within specific limits (typically between 10% of the rated voltage), and this reduces the amount of damping that can be provided by the compensator.

Moreover, the amount of injected reactive power needed to modulate the PCC voltage depends on the short circuit impedance of the grid seen at the connection point. Injection of active power, on the other hand, affects the PCC-voltage angle (transmission lines are effectively reactive) without varying the voltage magnitude significantly. The control of STATCOM with energy storage (named hereafter as E-STATCOM) for power system stability enhancement has been discussed in the literature [10]–[12]. 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) [9], 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. Thanks to the selected local signal quantities measured in the system, the control strategy optimizes the injection of active and reactive power to provide uniform damping at various locations in the power system. It will be shown that the implemented control algorithm is robust against system parameter uncertainties. For this, a modified recursive least square (RLS)-based estimation algorithm as described in [13], [14] will be used to extract the required control signals from locally measured signals. Finally, the effectiveness of the proposed control strategy will be validated via simulation and experimental verification.

II. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Because of the fast-switching characteristic of power converters, STATCOM provides much faster response as compared to the SVC. In addition, in the event of a rapid change in system voltage, the capacitor voltage does not change instantaneously; therefore, STATCOM effectively reacts for the desired responses. For example, if the system voltage drops for any reason, there is a tendency for STATCOM to inject capacitive power to support the dipped voltages.

STATCOM is capable of high dynamic performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances.

Moreover, much research confirms several advantages of STATCOM. These advantages compared to other shunt compensators include:

• Size, weight, and cost reduction
• Equality of lagging and leading output
• Precise and continuous reactive power control with fast response
• Possible active harmonic filter capability

STRUCTURE OF STATCOM

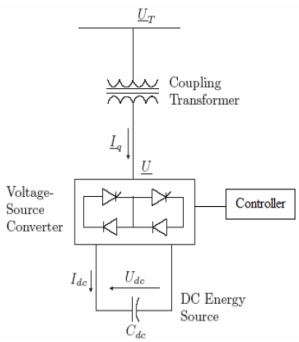

Fig.1.Structure of STATCOM

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Basically, STATCOM is comprised of three main parts a voltage source converter (VSC), a step-up coupling transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters.

III. SYSTEM MODELING AND 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.

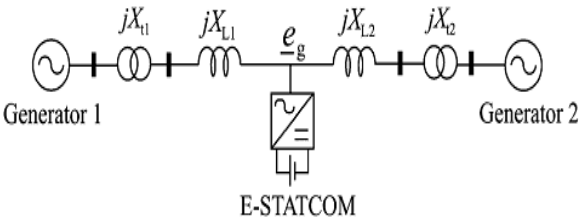

Fig.2. Simplified two-machine system with E-STATCOM.

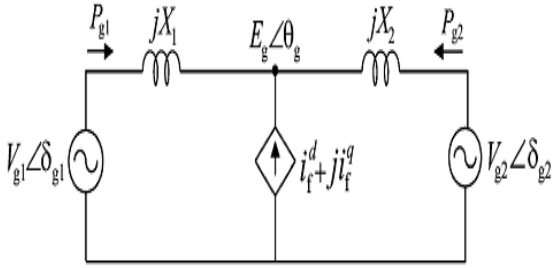

Fig. 3. Equivalent circuit for two-machine system with E-STATCOM.

The synchronous generators are modeled as voltage sources of constant magnitude and dynamic rotor angles behind a transient reactance .The transmission system consists of two transformers represented by their equivalent leakage reactance and a transmission line with equivalent reactance .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 [14]. For analysis purpose, the electrical connection point of the converter along the transmission line is expressed by the parameter as

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

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. 4. 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 depends on the type of outer loop control. The control algorithm is implemented in -reference frame where a phase-locked loop (PLL) [15] is used to track the grid-voltage angle from the grid-voltage vector . By synchronizing the PLL with the grid-voltage vector, the -and -components of the injected current (and) control the injected active and reactive power, respectively. In the notation in Fig. 2, denotes the corresponding reference signals.

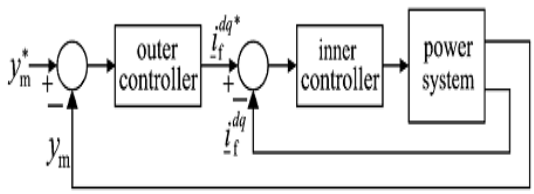

Fig. 4. Block diagram of the control of E-STATCOM.

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

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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. Therefore, the E-STATCOM can be modeled as a controlled ideal current source, as depicted in the equivalent circuit in Fig. 3, for analysis purpose.

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 and represent the change in active power from the corresponding generators due to injected active power and reactive power ,respectively. ,

The initial steady-state PCC voltage magnitude and generator rotor angles correspond to the operating point where the converter is in idle mode. A derivation to the expressions in (2) is given in the Appendix. 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.

The controller of a STATCOM operates the converter in a particular way that the phase angle between the converter voltage and the transmission line voltage is dynamically adjusted and synchronized so that the STATCOM generates or absorbs desired VAR at the point of coupling connection. Figure 3.4 shows a simplified diagram of the STATCOM with a converter voltage source __1*E* and a tie reactance, connected to a system with a voltage source, and a Thevenin reactance, $XTIEX\_THV_{TH}$.

IV. MODES OF OPERATION

There are two modes of operation for a STATCOM, inductive mode and the capacitive mode. The STATCOM regards an inductive reactance connected at its terminal when the converter voltage is higher than the transmission line voltage. Hence, from the system's point of view, it regards the STATCOM as a capacitive reactance and the STATCOM is considered to be operating in a capacitive mode. Similarly, when the system voltage is higher than the converter voltage, the system regards an inductive reactance connected at its terminal. Hence, the STATCOM regards the system as a capacitive reactance and the STATCOM is considered to be operating in an inductive mode

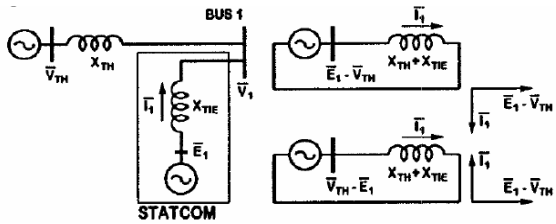

Fig.5.STATCOM operating in inductive or capacitive modes

In other words, looking at the phasor diagrams on the right of Figure 3.4, when1*I*, the reactive current component of the STATCOM, leads (*THVE*−1) by 90º, it is in inductive mode and when it lags by 90º, it is in capacitive mode.

This dual mode capability enables the STATCOM to provide inductive compensation as well as capacitive compensation to a system. Inductive compensation of the STATCOM makes it unique. This inductive compensation is to provide inductive reactance when overcompensation due to capacitors banks occurs. This happens during the night, when a typical inductive load is about 20% of the full load, and the capacitor banks along the transmission line provide with excessive capacitive reactance due to the lower load. Basically the control system for a STATCOM consists of a current control and a voltage control.

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IV-A. Current Controlled STATCOM

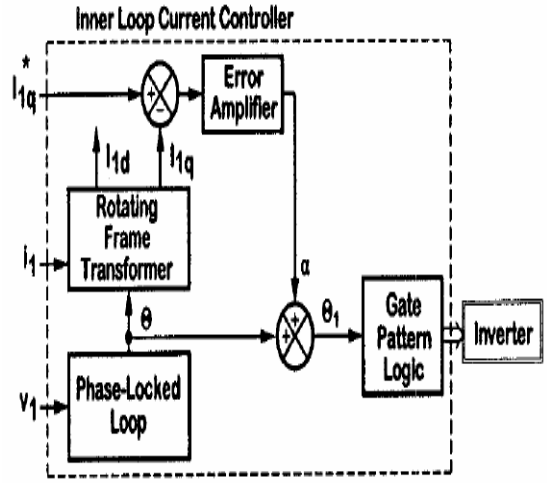

Fig.6.Current controlled block diagram of STATCOM

Figure above shows the reactive current control block diagram of the STATCOM. An instantaneous three-phase set of line voltages, v_l, at BUS 1 is used to calculate the reference angle, θ, which is phase-locked to the phase a of the line voltage, v_{la}. An instantaneous three-phase set of measured converter currents, i_l, is decomposed into its real or direct component, I_{1d}, and reactive or quadrature component, I_{1q}, respectively.The quadrature component is compared with the desired reference value, I_{1q}^* and the error is passed through an error amplifier which produces a relative angle, α, of the converter voltage with respect to the transmission line voltage.

The phase angle, θ_1, of the converter voltage is calculated by adding the relative angle, α, of the converter voltage and the phase – lock-loop angle, θ. The reference quadrature component, I_{1q}^*, of the converter current is defined to be either *positive* if the STATCOM is emulating an inductive reactance or *negative* if it is emulating a capacitive reactance. The DC capacitor voltage, v_{DC}, is dynamically adjusted in relation with the converter voltage. The control scheme described above shows the implementation of the inner current control loop which regulates the reactive current flow through the STATCOM regardless of the line voltage.

IV-B. Voltage Controlled STATCOM

In regulating the line voltage, an outer voltage control loop must be implemented. The outer voltage control loop would automatically determine the reference reactive current for the inner current control loop which, in turn, will regulate the line voltage.

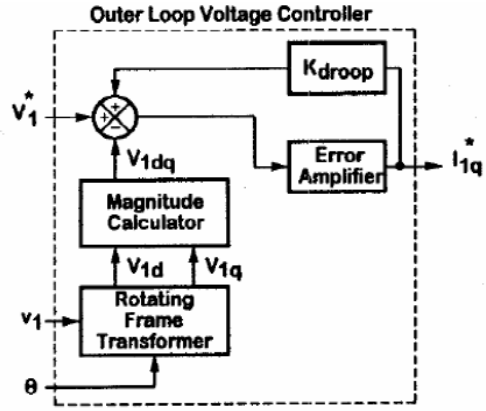

Fig.7.Voltage controlled block diagram of STATCOM

Figure 7 shows a voltage control block diagram of the STATCOM. An instantaneous three-phase set of measured line voltages, v_1, at BUS 1 is decomposed into its real or direct component, V_{1d}, and reactive or quadrature component, V_{1q}, is compared with the desired reference value, V_1^*, (adjusted by the droop factor, K_{droop}) and the error is passed through an error amplifier which produces the reference current, I_{1q}^*, for the inner current control loop. The droop factor, K_{droop}, is defined as the allowable voltage error at the rated reactive current flow through the STATCOM.

V. CONTROLLER

V-A. P-I CONTROLLER

P-I controller is mainly used to eliminate the steady state error resulting from P controller. However, in terms of the speed of the response and overall stability of the system, it has a negative impact. This controller is mostly used in areas where speed of the system is not an issue. Since P-I controller has no ability to predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations. If applied, any amount of I guarantees set point overshoot.

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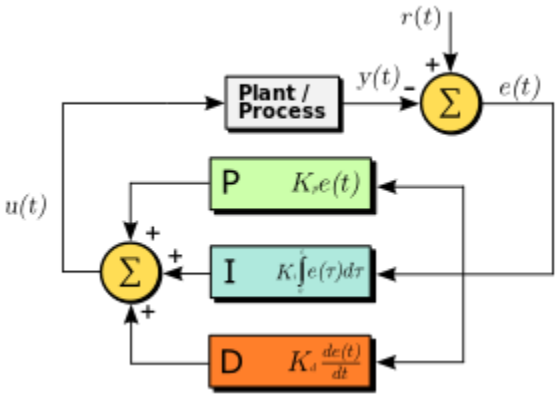

Fig.8: PID controller

A proportional–integral–derivative controller (PID controller) is a control loop feedback mechanism(controller) commonly used in industrial control systems. A PID controller continuously calculates an error values the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error over time by adjustment of a control variable, such as the position of a control valve, adamper, or the power supplied to a heating element, to a new value determined by a weighted sum.

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

where

K_p: Proportional gain, a tuning parameter
K_i: Integral gain, a tuning parameter
K_d: Derivative gain, a tuning parameter
e: Error $= SP - PV$
t: Time or instantaneous time (the present)
τ: Variable of integration; takes on values from time 0 to the present t.

Equivalently, the transfer function in thelaplace domain the controller is

$$L(s) = K_p + K_i/s + K_d s$$

Where
s: complex number frequency

V-B. PROPORTIONAL TERM:

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain constant.

The proportional term is given by:

$$P_{\text{out}} = K_p\, e(t)$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. Tuning theory and industrial practice indicate that the proportional term should contribute the bulk of the output change.

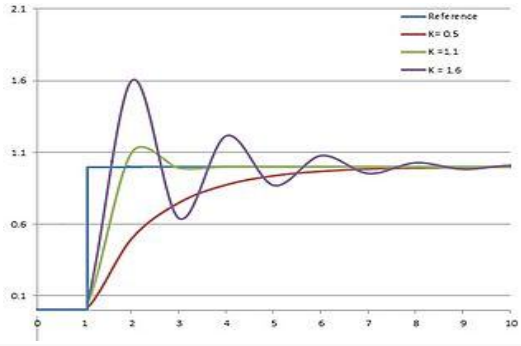

Fig.9: Plot of PV vs time, for three values of K_p (K_i and $K_d$held constant)

INTEGRAL TERM:

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain (K_i) and added to the controller output.

The integral term is given by:

$$I_{\text{out}} = K_i \int_0^t e(\tau)\, d\tau$$

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The integral term accelerates the movement of the process towards set point and eliminates the residual steady-state error that occurs with a pure proportional controller. However, since the integral term responds to accumulated errors from the past, it can cause the present value to overshootthe set point value.

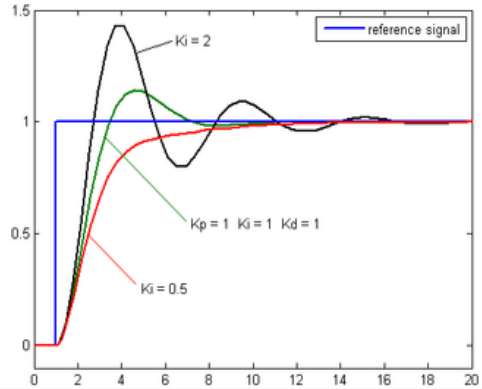

Fig.10: Plot of PV vs time, for three values of K_i (K_p and $K_d$held constant)

VI. 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 Madman's, 'min' operator. v. Defuzzification using the height method.

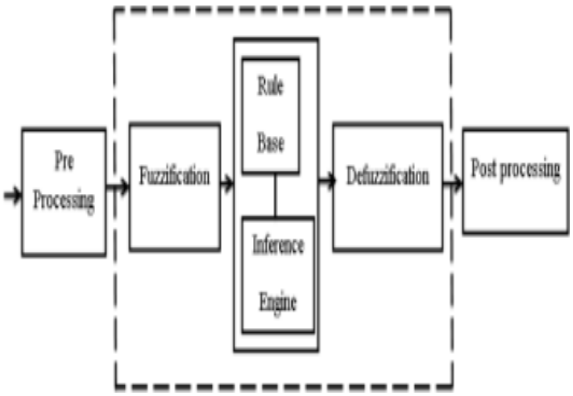

Fig.11. Fuzzy logic controller

Fuzzification:

Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the shape of membership CE(k) E(k) function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor

Change In Error	Error						
	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Table1. Fuzzy Rules

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular E(k) input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \qquad (14)$$

$$CE(k) = E(k) - E(k-1) \qquad (15)$$

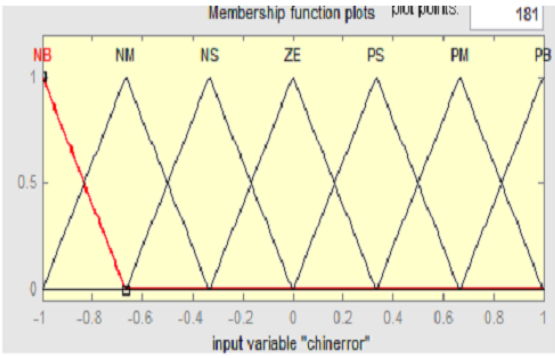

Fig.12. Membership functions

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Inference Method:

Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification:

As a plant usually requires a non-fuzzy value of control, a Defuzzification stage is needed. To compute the output of the FLC, „height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output.

The set of FC rules are derived from $u=-[\alpha E + (1-\alpha)*C]$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. set of FC rules is made using Fig.(b) is given in Table 1.

The membership function editor:

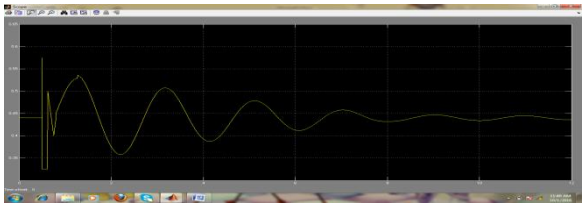
The Membership Function Editor shares some features with the FIS Editor. In fact, all of the five basic GUI tools have similar menu options, status lines, and Help and Close buttons. The Membership Function Editor is the tool that lets you display and edit all of the membership functions associated with all of the input and output variables for the entire fuzzy inference system. Fig.6 shows the Membership Function Editor.

You can first use the mouse to select a particular membership function associated with a given variable quality, (such as poor, for the variable, service), and then drag the membership function from side to side. This will affect the mathematical description of the quality associated with that membership function for a given variable. The selected membership function can also be tagged for dilation or contraction by clicking on the small square drag points on the membership function, and then dragging the function with the mouse toward the outside, for dilation, or toward the inside, for contraction. This will change the parameters associated with that membership function.

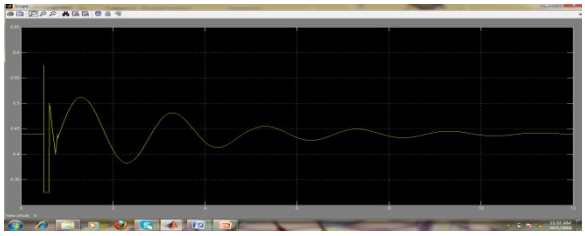
1. curve to rancid. To adjust the shape of the membership function, either use the mouse, as described above, or type in a desired parameter change, and then click on the membership function. The default parameter listing for this curve is [0 0 1 3].
2. Name the curve with the rightmost trapezoid, delicious, and reset the associated parameters if desired.

VII. RESULTS

BUS 7



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 7P inj



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 7Pinj&Qinj

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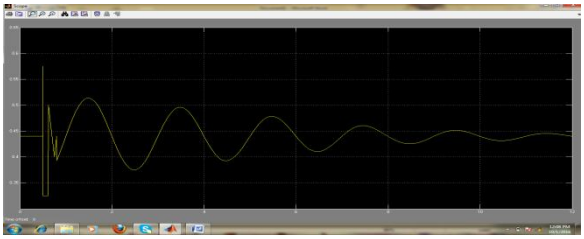
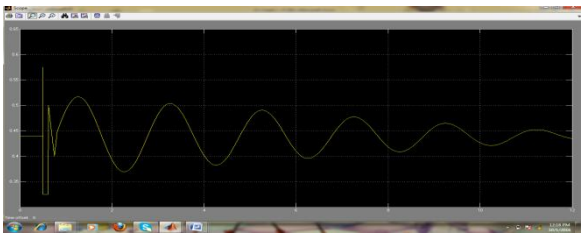
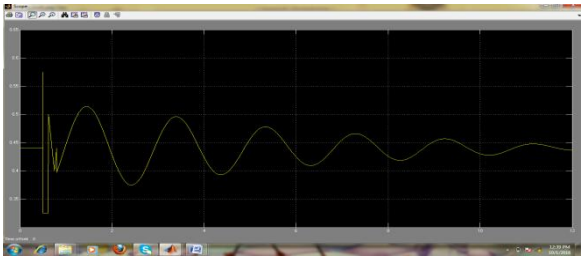


Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 7Qinj

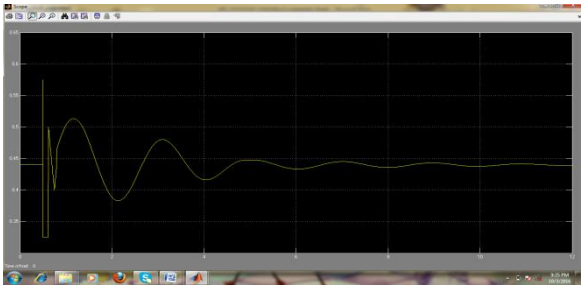


Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 7with out POD.

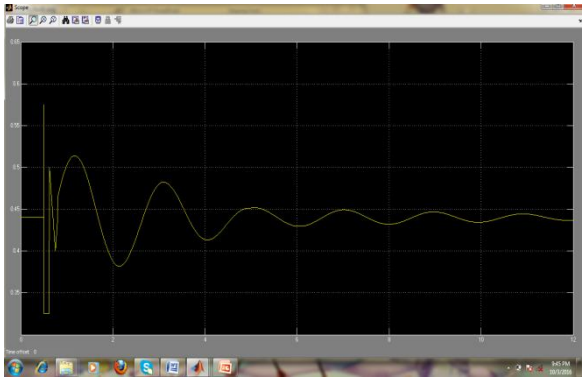
BUS-8



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 8P inj



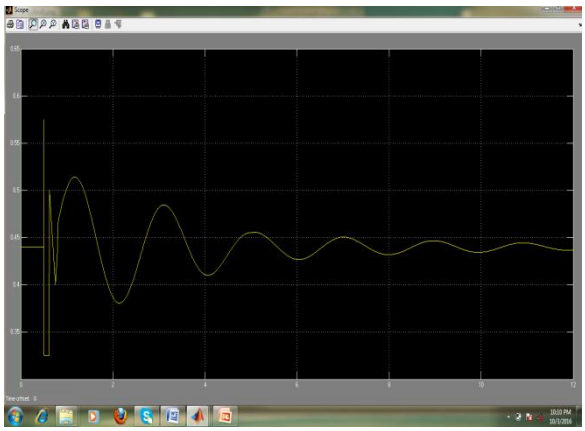
Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 8 Pinj&Qinj



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 8 Qinj

Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 8 with out POD.

BUS-9



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 9P inj

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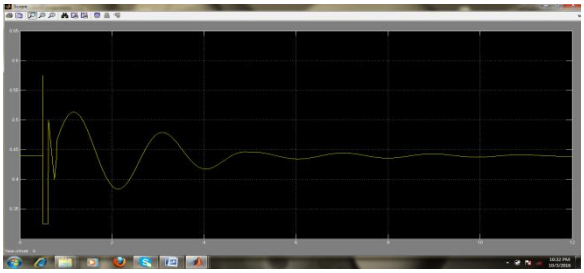
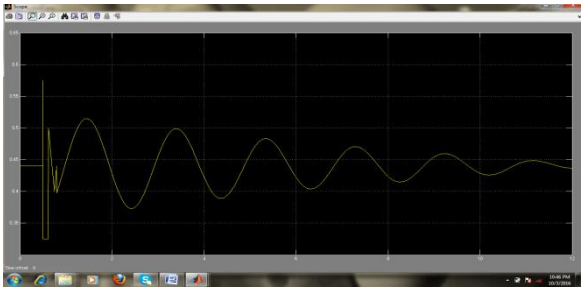
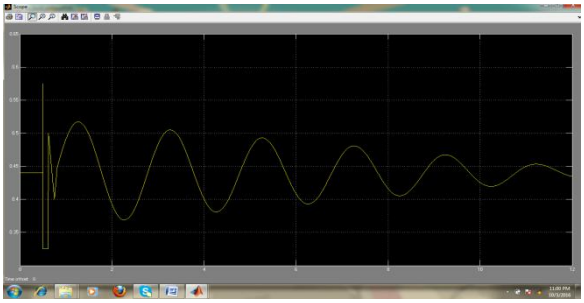


Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 9 Pinj&Qinj



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 9 Qinj



Measured transmitted active power output following a three-phase fault with E-STATCOMconnected at bus 9 with out POD

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 estimator enables a fast, selective and adaptive estimation of signal components at the power oscillation frequency. The dynamic performance of the POD controller to provide effective damping at various connection points of the E-STATCOM has been validated through simulation as well as experimental verification. The robustness of the control algorithm against system parameter changes has also been proven through experimental tests. Furthermore, using the frequency variation at the E-STATCOM connection point as the input signal for the active power modulation, it has been shown that active power injection is minimized at points in the power system where its impact on POD is negligible. This results in an optimal use of the available energy source.

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