http://dx.doi.org/10.5755/j01.eee.20.4.4940 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392–1215, VOL. 20, NO. 4, 2014

A Novel Robust STATCOM Control Scheme for Stability Enhancement in Multimachine Power System

A. Ganesh[1], R. Dahiya[2], G. K. Singh[3]
[1]Department of Electrical Engineering, M. M. University, Mullana, India
[2]Department of Electrical Engineering, NIT Kurukshetra, India
[3]Department of Electrical Engineering, IIT Roorkee, India
aman_ganesh@rediffmail.com

***Abstract*—The paper presents a systematic mathematical approach for designing a regulator for a STATCOM connected to a multimachine power system for improving the voltage profile during different operation conditions. The paper addresses the need for redefining the controller and generating a control signal to effectively allow the STATCOM to react with higher reactive support during dynamic disturbances. An auxiliary wide area damping controller is also proposed to supplement a fixed structure controller for the proposed STATCOM to improve the angular stability of the selected power system. The input signals for the proposed controllers are selected from the network parameters with highest participation factor to damp out the local modes of oscillations. The effectiveness of the proposed scheme is tested on IEEE 12 bus system and compared with conventional STATCOM control scheme.**

***Index Terms*—STATCOM, PI controller, voltage regulation, inter area low frequency oscillation.**

I. INTRODUCTION

STATCOM are used to increase the transmittable power and with the use of this reactive shunt compensation technique voltage regulation is achieved with the improvement in the transient stability and damping of the power oscillations in a given power network [1]. Many control schemes and topologies have been reported in literature for improving the regulation property of the STATCOM in terms of voltage and power under different applications either by using voltage source converter or current source converter with the use of PI controller as regulator for AC system voltage, the DC voltage and the current regulator under dynamic conditions of fault and loading. Different strategies involving PI controller as the heart of the control scheme can be found in literature which involves either a typical double loop PI control strategy using fixed gain or decoupled PI controller for regulating the voltage at PCC [2]–[9] and balancing the DC link voltage**.** The conventional PI control scheme is based on linearization of the system equation build around given operating conditions or operating point. The uncertainty created in the power system due to change in operating conditions such as fault or load switching the PI controller gives inferior performance. To have the satisfactory dynamic response, robust, adaptive and some nonlinear techniques using ANN, fuzzy logic, Genetic Algorithm and Particle Swarm Optimization techniques based on PI controller for the STATCOM have been forwarded [10]–[17]. Although published literatures had scarce information about the performance of the integrator of the PI controller [4], the new information is being explored in this research work. The integrator of the PI controller as being unstable system saturates and integrates to the large values; thus it gives ambiguous/erroneous results. So a new and robust control scheme is proposed to overcome this uncertainty by manifesting a new signal to the integrator that minimizes the sensitivity of the system to the changes and guarantees the better expected result.

Apart from using the conventional STATCOM controller based on linearized system equation [18]–[24] for improving the angular stability different robust schemes such as $H2/H_\infty$ [25]**,** LMI methods [26] are also reported in literature, which checks upon the stability of the selected signal based on different criterion such as using joint controllability-observability index [26]. A selection scheme based on eigenvalue sensitivity expressed in terms of participation factor is presented that identifies the parameters of the wide area measured signal available in the multimachine system as the input to the auxiliary controller, whose output is used as the stabilization signals to the STATCOM line voltage controller for damping out the low frequency oscillations.

This paper proposes a novel control scheme and structure for enhancing both the transient and angular stability with both complete mathematical and analytical descriptions. The effectiveness of the proposed scheme has been tested on IEEE 12 bus system and is compared with conventional STATCOM controller. MatLab/Simulink and PSAT simulations are carried out for the validation of the proposed scheme.

Manuscript received August 13, 2013; accepted January 26, 2014.

II. STATCOM STRUCTURE

The nonlinear STATCOM equation of the VSC based STATCOM described in *d-q* reference frame [27] are given by:

$$v_d = Ri_d + L\frac{di_d}{dt} - \mu L i_q + v_{in}, \tag{1}$$

$$v_q = Ri_q + L\frac{di_q}{dt} + \mu L i_q + v_{in}, \tag{2}$$

$$C\frac{dV_{dc}}{dt} = \frac{3}{2}(S_d i_d + S_q i_q), \tag{3}$$

where i_d and i_q are injected STATCOM currents, C is the equivalent capacitance of the dc bus capacitors, V_{dc} is the voltage across the DC capacitor, R and L represent the coupling transformer resistance and inductance, ω: synchronous angular speed of the network voltage at the fundamental system frequency *f*.

The STATCOM operation can be divided into three level controls:

A. First Level Control Design

This level is responsible for determining the power exchange between the STATCOM and the power system. It has two tier controls. The first is the frequency control which controls the power system frequency by modulating the active and reactive output current i.e. i_d and i_q. The second is the voltage control which generates the voltage reference signal V_r set by controlling i_q which is varied in accordance to the frequency deviation, which directly represents the power oscillation of the Power System. The frequency signal is derived from the positive sequence components of the ac voltage vector measured at the PCC of the STATCOM, through a PLL. The control law is such that when the generator accelerates, the frequency deviation becomes positive to counter this voltage at the PCC is forced to reduce and vice-versa control is exercised when generator decelerates this is done by exchanging power with the system.

B. Second Level Control Design

This level actually allows the power exchange between the STATCOM and the AC system by dynamically tracking the reference values set by the first level. This level control design is based on a linearization of the state-space averaged mathematical model of the STATCOM in *d-q* coordinates [27].

C. Third Level Control Design

It consists of line synchronization module that generates the modulation index and phase by converting the voltage v_{dq}^* to modulation index *m* and phase phi that defines the switching of VSC and injects the voltage in phase with the line voltage at PCC .The phase tracking is done by using unit vectors generated by the PLL.

III. DESIGNING THE CURRENT CONTROLLER

A. Transfer Function of the Voltage Source Inverter

Considering the above MIMO system and using the above set as combination of two SISO systems the identical d-axis (as is q-axis) the transfer function obtained is

$$\frac{id(s)}{vd(s)} = \frac{1}{(R+sL)}. \tag{4}$$

For proper synchronization the impedance has to be represented in synchronous frame too. If y^s is a general space vector with θ = ωt, its transformation in synchronous coordinates is

$$y_{dq} = y^s e^{-j\bar{}}. \tag{5}$$

The time derivative of (5) is transformed as (notations, derivative operation p = d/dt)

$$\frac{dy^s}{dt} = \frac{d(e^{j\bar{}}\, y_{dq})}{dt} = e^{j\bar{}}\,(p + j\mu)y_{dq}. \tag{6}$$

In the Laplace domain, the following substitution is made as s → s + jω. This implies that the complex impedance of an inductor in synchronous coordinates is represented as

$$Z(s) = (s + jw)L. \tag{7}$$

So the modified identical d-axis (as is q-axis) transfer function in reference to (4) obtained is

$$\frac{id(s)}{vd(s)} = \frac{1}{(R+sL+jwL)}. \tag{8}$$

Now the aim is to find the synchronous coordinate equation, for this (1) and (2) has to be modified.
(Notations $\underline{x} = x_{dq} = xd + jxq, \underline{E} = v_{dq}, \underline{v} = v_{indq}$) .

$$L\frac{d\underline{i}}{dt} = \underline{E} - (R + jwL)\underline{i} - \underline{v}. \tag{9}$$

And the system transfer function $\underline{G}(s)$ is given by

$$\underline{G}(s) = \frac{\underline{i}}{\underline{v}} = -\frac{1}{R+sL+jwL}. \tag{10}$$

B. Cross Coupling Cancellation

A PI current controller traces the performance for the coupled system described by equations v_d and v_q. The first step in the controller design is to cancel the cross coupling initiated by the term $j\omega L\underline{i}$ (since multiplication by *j* maps the *d* axis on *q* axis and vice versa). With the accurate estimation of *L* this can be achieved. $\overline{L}$ is estimated for *L*. For high performance and accuracy current tracking we need to cancel this cross coupling. Selecting *v* as (9) and estimating the value of E as $\vec{E}$ we have

$$\underline{v} = -\underline{v}' + \overline{\underline{E}} - jw\overline{L}\underline{i}. \tag{11}$$

If $\vec{L} = L$ and $\vec{E} = E$, then

$$\underline{i} = \frac{\underline{v}'}{R + sL}. \quad (12)$$

With $\underline{G}'(s)$ the decoupled system transfer function from $\underline{v}'$ to $\underline{i}$ we have

$$\underline{G}'(s) = \frac{\underline{i}}{\underline{v}'} = \frac{1}{R + sL}. \quad (13)$$

C. Controller Transfer Function

The designed controller has to be directly parameterized in terms of the plant model parameters and the desired closed loop bandwidth. For the transfer function defined by (13) the generalized controller transfer function will be of the type

$$G_i(s) = \frac{\sim^n}{(s + \sim)^n - \sim^n} G_s^{-1}(s), \quad (14)$$

where $G_i(s)$, hence is a low pass filter with bandwidth α and $G_s(s)$ is the estimation of the plant and n is the order of G. For this a PI controller is enough

$$G_i(s) = k_p + \frac{K_i}{s}. \quad (15)$$

Estimating (14) in terms of (15) the obtained PI coefficients are $k_p = \sim \bar{L}$ *and* $k_i = \sim \bar{R}$.

For this inner current control loop, the bandwidth α is selected smaller than a decade below the sampling frequency.

D. Decoupled Current Control

In order to establish the decoupled current control continue with (9). We define $\underline{I}$**,** complex integrator state variable as $\frac{dI}{dt} = \varepsilon$, we have

$$\underline{v} = (\overline{E_d} + j\overline{E_q}) - k_p(\pounds d + j\pounds q) - $$
$$-ki(I_d + jI_q) - jw\bar{L}(i_d + ji_q). \quad (16)$$

The reference voltage is then computed by writing the real and the imaginary part:

$$v_d^* = \bar{E}d - k_p \pounds d - k_i i_d + w\bar{L}i_q, \quad (17)$$

$$v_q^* = \bar{E}q - k_p \pounds q - k_i i_q + w\bar{L}i_d, \quad (18)$$

where i_d and i_q determines the active and reactive power flows.

E. Proposed Control Scheme

For large step variation of the d-current, the controller might demand a too large voltage. Considering v as the reference voltage, the PI controller output is expressed as

$$v(t) = k_p \pounds(t) + k_i I(t), \quad (19)$$

where $\frac{dI}{dt} = \pounds$.

The difficulty arises once v becomes limited. In order to avoid this, the integrator part I should not be updated with too large error ε. For this the integrator is fed with another error $\bar{\varepsilon}$, so that $v = \bar{v}$

$$\bar{v}(t) = k_p \bar{\pounds}(t) + k_i I(t). \quad (20)$$

Then by writing the difference $\bar{v} - v$ the error is

$$\bar{\pounds} = \pounds + \frac{\bar{v} - v}{k_p}. \quad (21)$$

For the decoupled controller (17) and (18) can be expressed as

$$v_{dq}^* = \overline{E_{dq}} - k_p \pounds_{dq} - k_i i_{dq} + \mu \bar{L} i_d + \mu L i_q. \quad (22)$$

Now we call $\bar{v}$, the value of v_{dq}^* after some saturation is expressed as

$$v_{dq}^* = \overline{E_{dq}} - k_p \overline{\pounds_{dq}} - k_i i_{dq} + \mu \bar{L} i_d + \mu \bar{L} i_q. \quad (23)$$

By writing the difference $v_{dq}^* - \bar{v}$, the error $\overline{\pounds_{dq}}$ fed to the controller is

$$\overline{\pounds_{dq}} = \pounds_{dq} + \frac{v_{dq}^* - \bar{v}}{k_p}. \quad (24)$$

The advantage of using this robust control scheme is that from the updated output value of reference v_{dq}, the corresponding value of id and iq determines the active and reactive power flow with corresponding voltage regulation (explained in section II.A) which should be better in comparison to conventional control scheme for the selected bus.

The control scheme for STATCOM model developed is tested on IEEE 12 bus benchmark system as given in Fig. 1. From the load flow studies and dynamic stability studies carried out in PSAT toolbox in MatLab it was observed that the uncompensated system has low voltage at bus 4 and 5. So shunt compensation in form of STATCOM is applied at bus 4 which considerably improves the voltage level, as suggested by the simulation results.

IV. INTER AREA LOW FREQUENCY OSCILLATION DAMPING

The main objective of the STATCOM connected to the IEEE 12 bus- benchmark system at bus 4 was to regulate the voltage magnitude. But the other affected parameters of the considered power system because of the presence of the STATCOM are the active power flows through the neighbouring transmission lines and the speed deviations of the synchronous generators.

Because of the inertia constants of the generator local frequency swings are there. For damping out these low frequency oscillations, the controller has to counter the swings of the disturbed machine.

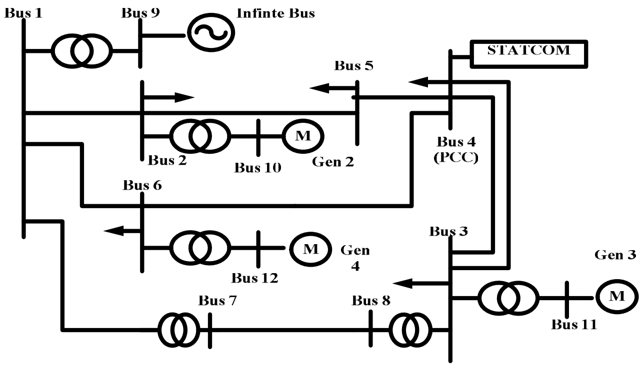

Fig. 1. IEEE 12 bus benchmark system.

A. Signal Selection from Wide Area Control

A simplified linearized method, dependent on the operating condition of the power system, is applied for introducing auxiliary signals to the STATCOM controller for improving the transient and dynamic behaviours of the power system, by controlling the network parameters in its neighbourhood. The state space representation of the power system can be expressed as

$$\Delta \dot{x}(t) = A\Delta x(t) + B\Delta u(t), \tag{25}$$

$$\Delta y(t) = C\Delta x(t) + D\Delta u(t), \tag{26}$$

where $\Delta x(t)$ and $\Delta y(t)$ are the state and output vector of dimension n and m respectively, A is the state matrix of dimension $n \times n$.

The eigenvalue analysis of the system shows that there are three modes of oscillations oscillating at different frequency owing to the presence of three synchronous generators as shown in Table I.

TABLE I. CRITICAL MODES OF OSCILLATION OF IEEE 12 BUS SYSTEM.

System modes	Damping (%)	Frequency (Hz)	Participation Factor		
			Δω2	Δω3	Δω4
-0.19 ± 4.982	3.81	0.792	0.459	0.0002	0.0021
-0.318 ± j7.436	4.27	1.183	0.0049	0.426	0.0451
-0.143 ± j4.449	3.21	0.708	0.016	0.0978	0.311

For the purpose of stabilizing the oscillations any of the available measured signals such as frequency and speed deviations of the generators, bus voltage, bus angle, line current, line active, and reactive power can be used as feedback signal. But in this paper only the speed deviation of the generator has been taken as input signal to the controller which helps in generating a new voltage reference control signal.

But among the available input signals, a selection has to be made so that the selected signal should have better damping to the critical modes of oscillation and should not affect the other modes. For this the participation factor has been used as an index for the selection of the stabilization signal. The participation factor helps to relate the participation of the respective state variable to the selected mode or in other words it relates the left and the right eigenvectors for identifying the relationship between the states and the modes. For any given eigenvalue λ_i of the state matrix A, assume ψ_i and ϕ_i to be the left and the right eigenvectors respectively. Then the participation factor *p*, for the kth element is defined as

$$p_{ki} = \phi_{ki}\psi_{ik}. \tag{27}$$

The participation of the generator speed deviations (Δω2, Δω3, Δω4) in the three oscillating modes is also shown in Table I. It is clear that the participation of Δω3 and Δω4 in first mode oscillating at frequency 0.792 Hz is low. While the participation of Δω2 in other two modes oscillating at the frequency of 1.183 Hz and 0.708 Hz respectively is relatively low in comparison to Δω3 and Δω4.

It can be attributed that generator 2 considerably being in the vicinity of the infinite bus has sufficient damping whereas damping is required for the other modes. Hence the respective speed deviations of generator 3 and 4 are selected as the obvious choice for selection of manipulating signal for the generation of the auxiliary signals.

B. External Controller Design for Damping Low Frequency Oscillation and Complete Control Scheme

The objective is to provide a robust frequency control scheme to effectively damp out the generator's low frequency oscillation. Upon the identification of power system parameter (Δω3 and Δω4) which actively participate in the system mode oscillating at some frequency owing to the presence of synchronous generator in the multimachine network, a differential filter is synthesized in conjunction with the fixed structure controller for a desired gain and phase characteristics of the frequency stabilizer for generating a new voltage reference control signal Vr* proportional to the selected feedback parameter. This added signal causes the iq* to vary around the operating point defined by Vr*.

A differential filter structure for a multimachine power system is to be synthesized that covers the interplant/local mode of oscillation (frequency range of 0.7 Hz to 2.0 Hz) and interarea mode of oscillation (frequency range of 0.1 Hz to 0.7 Hz respectively. The power system oscillations are damped out by rapidly exchanging active power with the utility system i.e. by controlling the output direct current id. Thus the reference of the STATCOM output current, id*, is directly derived from the frequency signal Δf derived from the positive sequence components of the ac voltage vector measured at the PCC of the STATCOM, through a phase locked loop (PLL). For this a band pass filter is used where tuning of the intermediate band filter is done at 0.7 Hz and high pass filter is tuned at 7 Hz which provides zero gain at high frequency and phase leading up to the resonant frequency. The resulting compensator controllers are combined to obtain frequency stabilizer with an adequate phase characteristic for all small frequency deviation modes. The resulting stabilizer signal is then passed through a final limiter for setting the reference id*. The complete proposed control scheme is shown in Fig. 2.

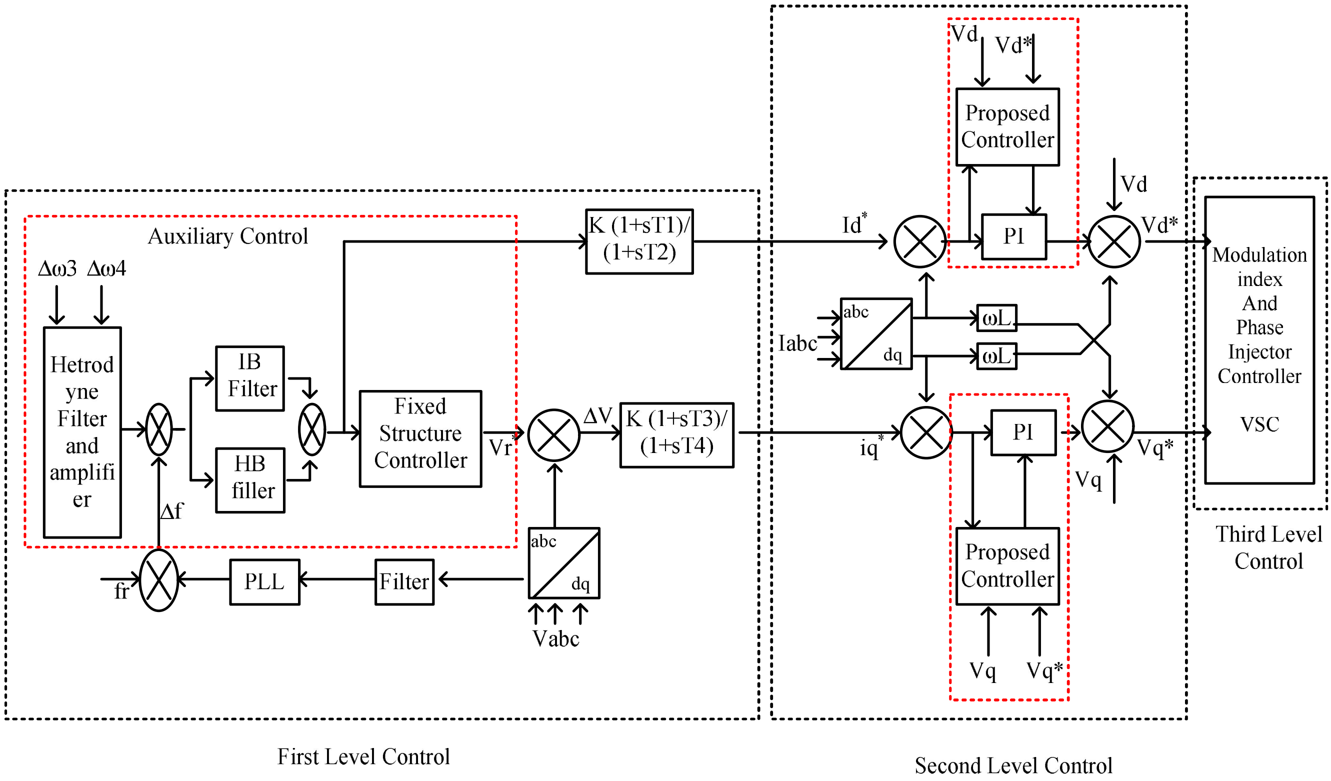

Fig. 2. Complete proposed control scheme.

V. RESULTS AND DISCUSSION

The system considered is a standard IEEE 12 bus benchmark power system. After completing load flow study for the selected network bus 4 has the lowest bus voltage of 0.95 p.u. The STATCOM is connected to bus 4 for the purpose of improving the voltage stability and to control the voltage and the active reactive power flow during the dynamic disturbances.

A. Large Signal Disturbance: 3 Phase Fault Between Bus 4 and 5 and Load Variation at Bus 4

The Simulations are carried out to validate that the effectiveness of the proposed regulator described in section three against STATCOM with conventional PI control scheme. In order to analyse system performance and reactive power support under critical conditions**,** a general 3 phase to ground fault is applied to the middle of the parallel transmission line 3-4 connecting the STATCOM to the generator at t = 0.4 s for 100 ms (6 cycles) and the bus is loaded with switch capacitive and inductive load form t = 1.15 to 1.55 with a span switching of point twenty. The STATCOM operates in the reactive current reference control mode. Figure 3(a), shows the reactive current tracking. The good performance of the voltage regulation at the PCC of the STATCOM is evidently depicted, Fig. 3(d), by the compensators ability to inject or withdraw reactive power, Fig 3(c), into the network in response to the active oscillation in active power viz. load angle Fig 3(b). During the time when the transmission line active power (load angle) is increasing, reactive power injection into the network causes an increase in PCC voltage which opposes the change in active power. The power compensation depends upon the severity of the fault and loading conditions.

B. Dynamic Response of the Controller for Power Oscillation Damping

For the selected system of IEEE 12 bus benchmark system first the power flow analysis was carried out, it was found that there are three local oscillation modes corresponding to generators 3 and 4 as shown in Table I. Hence the selected power system does have inter area modes of oscillations but participation of generator 3 is more predominant hence a local stabilizer can't be installed for damping the existing oscillations. The fact that STATCOM can also be used to damp out the oscillation by controlling *iq* as explained earlier. The performance is compared when the system is there with conventional PI control scheme, STATCOM with proposed PI regulator and STATCOM with proposed PI regulator and auxiliary controller. The disturbance occurring in the power system causes electromechanical oscillations of the generator which have effect on the rest of the electric system. To maintain the system stability these oscillations have to be damped out. During disturbances the input mechanical energy appears as an increase in the kinetic energy of the system with the consequent increase in the speed of the unit. Because of the low resistive nature of the line the oscillations persists for a long time. The low frequency power swings influences the system frequency along with the rotor angle deviation the torque supplied by the machine and also the voltage profile of the bus. The simulations are carried out using the power flow analysis result that the midpoint voltage without STATCOM is 0.95 and the same is set as steady state value. The generator delivers 0.9 p.u. power to the system. The simulation results are shown in Fig. 4.

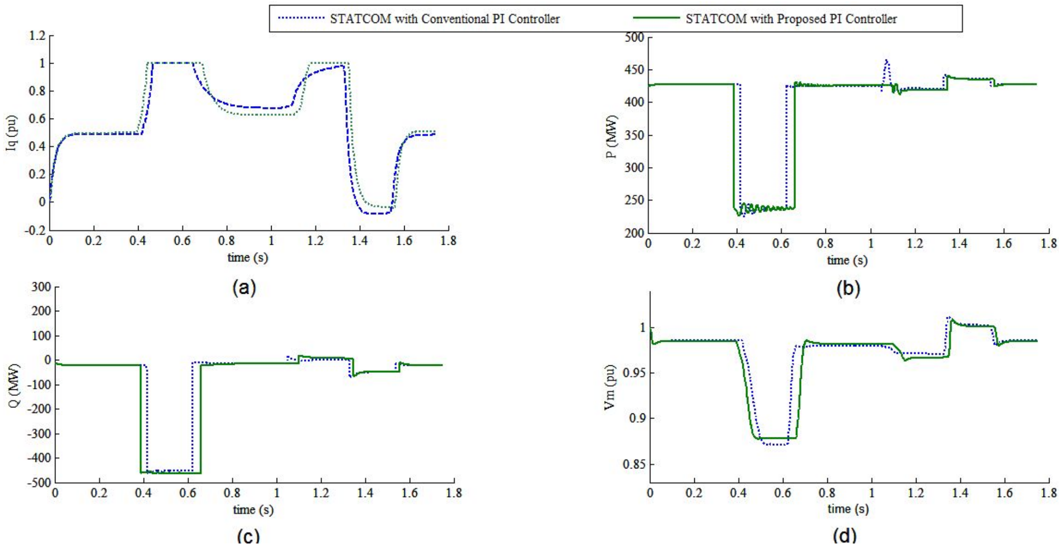

Fig. 3. Case-I (a) reference current tracking (b) active power oscillation (c) injected reactive power (d) voltage at PCC.

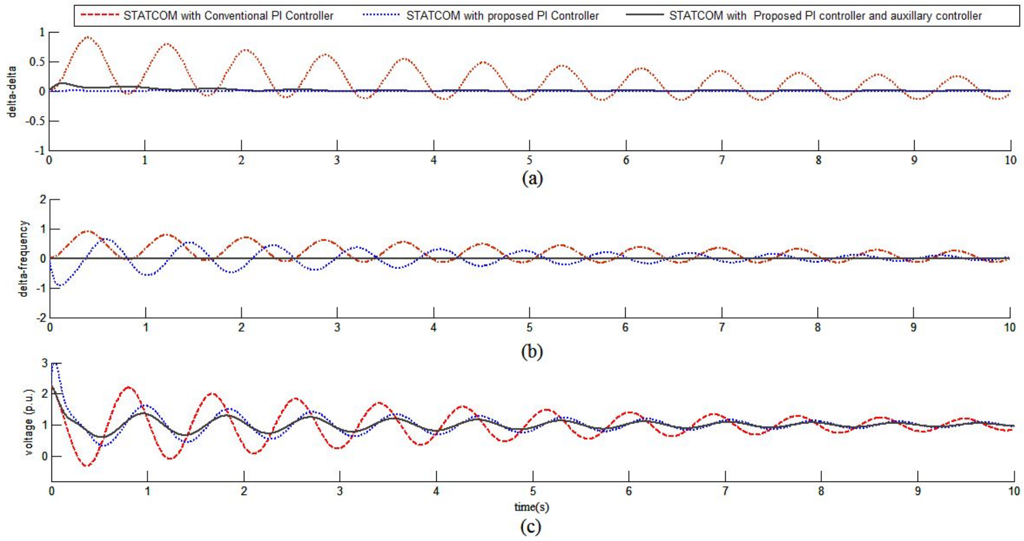

Fig. 4. Case-II (a) rotor angle variation (b) frequency (c) voltage profile.

VI. CONCLUSION

The paper has presented a STATCOM controller for achieving better transient and angular stability**.** The validity and performance of the proposed controller are evaluated on a multimachine system. The developed robust PI regulator improves the voltage profile of the system by providing better reactive power support during the contingencies conditions than the conventional controller where the integrator saturates to a higher value under disturbed dynamics by feeding the controller with additional input signal. An auxiliary controller in addition to STATCOM line voltage controller is also proposed to efficiently damp out the low frequency oscillations. The wide area signal selection for the auxiliary controller is done on the basis of eigenvalue sensitivity. It can be concluded from the simulation results that the scheme involving combined action of both the proposed regulator and auxiliary controller has the ability to efficiently damp out the present mode of oscillations and provides superior performance as compared to the conventional and proposed controller along with fixed structure controller.

REFERENCES

[1]. N. G. Hingorani, L. Gyugyi, *Undersatnding FACTS:Concepts and Technology of Flexible AC Transmission Systems*, Standard Publishers Distributors: New Delhi, 2001, pp. 135.

[2]. K. Wang, M. L. Crow, "Power system voltage regulation via STATCOM internal nonlinear control" *IEEE Trans. Power Sys.*, vol. 26, no. 3, pp. 1252–1262, 2011. [Online]. Available: http://dx.doi.org/10.1109/TPWRS.2010.2072937

[3]. Y. Han, Y. O. Lee, C. C. Chung, "Modified non-linear damping of internal dynamics via feedback linearisation for Static Synchronous Compensator" *IET Gener. Transm. Distrib.*, vol. 5, no. 9, pp. 930–940, 2011. [Online]. Available: http://dx.doi.org/10.1049/iet-gtd.2010.0551

[4]. W. L. Chen, Z. C. Li, C. Z. Xie, "Control of static synchronous compensator with supplementary damping enhancement for wind farm voltage regulation", *IET Gener. Transm. Distrib.*, vol. 5, no. 12, pp. 1211–1220, 2011. [Online]. Available: http://dx.doi.org/10.1049/iet-gtd.2011.0246

[5]. H. Zhou, G. Yang, J. Wang, H. Geng, "Control of a hybrid high-voltage DC connection for large doubly fed induction generator-based wind farms" *IET Renew. Power Gener.*, vol. 5, no. 1, pp. 36–47, 2011. [Online]. Available: http://dx.doi.org/10.1049/iet-rpg.2009.0171

[6]. V. Spitsa, A. Alexandrovitz, E. Zeheb, "Design of a robust state feedback controller for a STATCOM using a zero set concept", *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 456–467, 2010. [Online]. Available: http://dx.doi.org/10.1109/TPWRD.2009.2034828

[7]. B. S. Chen, Y. Y. Hsu, "A minimal harmonic controller for a STATCOM", *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 655–664, 2008. [Online]. Available: http://dx.doi.org/10.1109/TIE.2007.896266
[8]. B. S. Chen, Y. Y. Hsu, "An analytical approach to harmonic analysis and controller design of a STATCOM", *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 423–432, 2007. [Online]. Available: http://dx.doi.org/10.1109/TPWRD.2006.883016
[9]. S. Mohagheghi, Y. del Valle, G. K. Venayagamoorthy, R. G. Harley, "A proportional-integral type adaptive critic design-based neuro controller for a static compensator in a multimachine power system", *IEEE Trans. Ind. Electron*., vol. 54, no. 1, pp. 86–96, 2007. [Online]. Available: http://dx.doi.org/10.1109/TIE.2006.888760
[10]. V. K. Chandrakar, A. G. Kothari, "Comparision of RBFN and Fuzzy based STATCOM for transient stability improvement" in *Int. Aegean Conf. Electrical Machines and Power Electronics*, pp. 520–525, 2007.
[11]. S. Mohagheghi, G. K. Venayagamoorthy, R. G. Harley, "Fully evolvable optimal neurofuzzy controller using adaptive critic designs", *IEEE Trans. Fuzzy Syst.*, vol. 16, no. 6, pp. 1450–1461, 2008. [Online]. Available: http://dx.doi.org/10.1109/TFUZZ.2008.925910
[12]. S. Mohagheghi, R. G. Harley, G. K. Venayagamoorthy, "An adaptive Mamdani fuzzy logic based controller for STATCOM in a multimachine power system", in *Proc. ISAP*, 2005, pp. 228–233.
[13]. M. A. Zanjani, Gh. Shahgholian, S. Eshtehardiha, "Gain tuning PID and IP controller with an adaptive controller based on the genetic algorithm for improvement operation of STATCOM", in *Proc. 7th WSEAS Int. Conf. on Electric Power Systems, High Voltages, Electric Machines*, Venice, Italy, pp. 28–33, 2007.
[14]. N. Djagarov, Z. Grozdev, M. Bonev, P. Valkov, "Adaptive astatic modal regulator for STATCOM", in *Proc. of the 9th WSEAS Int. Conf. Power Systems (PS 2009)*, 2009, pp. 123–126.
[15]. S. A. Chatterjee, K. D. Joshi, "A Comparison of conventional, direct-output- voltage and Fuzzy-PI control strategies for D-STATCOM", in *Proc. Int. Symposium Modern Electric Power Systems*, Wroclaw, Poland, pp. 1–6, 2010.
[16]. Gang Yao, LiXue Tao, LiDan Zhou, Chen Chen, "State-feedback control of a current source inverter-based STATCOM", *Elektronika ir Elektrotechnika (Electronics and Electrical Engineering*), no. 3, pp. 17–22, 2010.
[17]. R. Cimbals, O. Krievs, L. Ribickis, "A static synchronous compensator for displacement power factor correction under distorted mains voltage conditions", *Elektronika ir Elektrotechnika (Electronics and Electrical Engineering*), no. 4, pp. 71–76, 2011.
[18]. Li Wang, Dinh-Nhon Truong, "Dynamic stability improvement of four parallel-operated PMSG-based offshore wind turbine generator fed to a power system using STATCOMs", *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 111–119, 2013. [Online]. Available: http://dx.doi.org/10.1109/TPWRD.2012.2222937
[19]. Li Wang, Chia-Tien Hsiung, "Dynamic stability improvement of an integrated grid-connected offshore wind farm", *IEEE Trans. Power Sys*., vol. 26, no. 2, pp. 690–698, 2011. [Online]. Available: http://dx.doi.org/10.1109/TPWRS.2010.2061878
[20]. A. H. Norouzi, A. M. Sharaf, "Two control schemes to enhance the dynamic performance of the STATCOM and SSSC," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 435–442, 2005. [Online]. Available: http://dx.doi.org/10.1109/TPWRD.2004.839725
[21]. N. Mithulananthan, C. A. Canizares, J. Reeve, G. J. Rogers, "Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 786–792, 2003. [Online]. Available: http://dx.doi.org/10.1109/TPWRS.2003.811181
[22]. A. Rohani, M. Reza Safari Tirtashi, R. Noroozian, "Combined design of PSS and STATCOM controllers for power system stability enhancement", *Journal of Power Electronics*, vol. 11, no. 5, pp. 734–742, 2011. [Online]. Available: http://dx.doi.org/10.6113/JPE.2011.11.5.734
[23]. D Harikrishna, Kamal Narayan Sahu, N. V. Srikanth, "Power system dynamic stability enhancement using Fuzzy controlled STATCOM", *Elektronika ir Elektrotechnika (Electronics and Electrical Engineering*), vol. 1, no. 2, pp. 72–78, 2011.
[24]. A. K. Yadav, H. Rathaur, A. K. Singh, "Static synchronous compensator (STATCOM) modeling for power oscillations damping", in *Int. Journal of Scientific and Research Publications*, vol. 3, no. 4, pp. 1–7, 2013.
[25]. Y. Zhang, A. Bose, "Design of wide-area damping controllers for interarea oscillations", *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1136–1143, 2008. [Online]. Available: http://dx.doi.org/10.1109/TPWRS.2008.926718
[26]. B. P. Padhy, S. C. Srivastava, N. K. Verma, "Robust wide-area Ts Fuzzy output feedback controller for enhancement of stability", in *IEEE Sys. Journal*, vol. 6, no. 3, pp. 426–435, 2013.
[27]. C. Schauder, H. Mehta, "Vector analysis and control of advanced staticVAR compensators", in *Proc. Inst. Elect. Eng*., vol. 140, no. 4, 1993, pp. 299– 306.