International Journal of Power Control Signal and Computation (IJPCSC)
Vol. 4 No. 2 April- June -2012
©gopalax journals,singapore
ISSN:0976-268X
Available at : http://ijcns.com

POWER QUALITY IMPROVEMENT USING SELF-TUNING PI CONTROLLED STATCOM BY PARTICLE SWARM OPTIMIZATION

K.PARVENTHAN
Department of Electrical and Electronic Engineering
Dr Pauls Engineering College
Villupurum Dist, Tamil nadu, India
raja_7372@yahoo.com

M.BALAMURUGAN
Department of Electrical and Electronic Engineering
Dr Pauls Engineering College
Villupurum Dist, Tamil Nadu, India
balasingar.m@gmail.com

***Abstract*— In recent years, there has been an increasing interest on applying advanced and intelligent control designs in power engineering area. As a heuristic optimization technique, Particle Swarm Optimization (PSO) is used for tuning the parameters of the STATCOM. Regulating the DC capacitor voltage in STATCOM is a common task and can improve the system dynamic. The nonlinear control is based on exact linearization via feedback. A PI controller exists in this control system to regulate the capacitor voltage. In conventional scheme, the trial and error method has been used to determine PI controller coefficients. In this project, the effect of PI gains on responses of V_{dc} , I_{dc} and Modulation Index (M) is presented. The exact calculation of optimized PI coefficients can be carried out to reduce disturbances and steady state error in DC link voltage.**

An efficient formula for the estimation of system load impedance using real-time measurements is derived. Based on the estimated system load, a PSO algorithm, which takes the best particle gains, the best global gains, and previous change of gains into account, is employed to reach the desired controller gains. To demonstrate the effectiveness of the proposed PSO self-tuning PI controller for a STATCOM, experimental results for a system under different loading conditions are presented. Results from the self-tuning PI controller are compared with those from the fixed-gain PI controllers.

Keywords-
STATCOM, FACTS, self-tuning PI controller, Particle swarm optimization, Voltage Source Converter MATLAB / SIMULINK

I. INTRODUCTION

Recent developments in power electronics play a major role in the accomplishment of more efficient power systems. The main reason for that is the ability of power electronic devices to control power flow in transmission lines. The technology of flexible AC transmission systems, which are based on

power electronics, is Flexible AC Transmission Systems (FACTS) have become very important applications of power electronics in controlling power flow advancing and it has different applications in power control.

They were the solution to the difficulties that were arising with the geographically uneven growing power demand. FACTS met the transmission system requirement to use the existing power facilities without decreasing system availability and security. In addition, the use of FACTS provides voltage support to prevent voltage collapses when the electricity network is under heavy loading. The main objectives of FACTS are to increase transmission capacity of lines and to control the power flow over chosen transmission routes [1].

FACTS offer the possibility of meeting many recent power demands. FACTS devices are routinely employed in order to enhance the power transfer capability of the otherwise underutilized parts of the interconnected network [2].FACTS could be connected in series with the power system
Working as a controllable voltage source or in shunt with the power system working as a controllable current source. The STATic synchronous COMpensator (STATCOM) is a shunt FACTS device and it was introduced and developed in the last decade. It is used to regulate voltage values at different points in the transmission lines.

In the literature, decoupled control of *d*- and *q*-axis currents and voltages has been proposed to regulate the dc capacitor voltage and the ac system (load) voltage, respectively, in STATCOM controller design [3]–[6]. Proportional-integral (PI) controllers have been designed for the ac system voltage regulator, the dc voltage regulator, and the current regulators. Satisfactory dynamic responses have been reported for the STATCOM with PI controllers.

International Journal of Power Control Signal and Computation (IJPCSC)
Vol. 4 No. 2 April- June -2012
©gopalax journals,singapore
ISSN:0976-268X
Available at : http://ijcns.com

In the fixed-gain PI controller [3]–[6], the controller gains for the STATCOM were usually designed based on a Linearized system equation for the system under a nominal load condition [3]–[6].

These controller gains remained fixed in daily operation of the STATCOM. Since system load changes with time in daily operation of the STATCOM, the system matrix, the closed-loop Eigen values, and the dynamic performance will change.
Therefore, to maintain good dynamic responses at all possible loading conditions, the controller gains need to be adapted.

II POWER SYSTEM CONFIGURATION WITH STATCOM

Figure 1 shows the configuration of the system with STATCOM connected in load bus. A three phase non linear load (a rectifier with resistor) is connected in load bus. Where Rp represents the 'ON' state resistance the switches which are in Voltage Source Inverter including coupling transformer leakage resistance, L_p represents the coupling transformer leakage inductance. A Voltage Source Inverter is the core element of the STATCOM.it generates a balanced and controlled three phase voltage V_p. Rs+jωLs represents the source impedance whereas Rt+jωLt represents the line impedance.

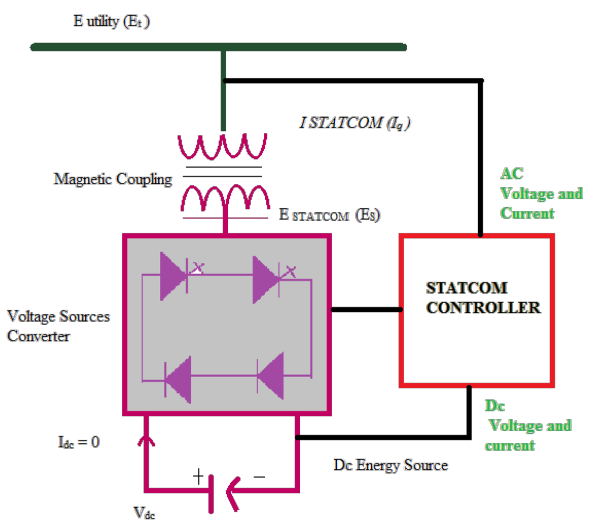

Figure 1: Configuration of the system with a STATCOM

The contents of this paper are as follows. First, the configuration of the system with a STATCOM is described. The dynamic equations for the load, the VSC ac-side system, and the VSI dc-side system are then derived. When the dynamic equations for the system are Linearized around a nominal loading condition, we can proceed to design a fixed-gain PI controller for the STATCOM using the Linearized state equations. Then, a self-tuning PI controller for the STATCOM is designed using the PSO method

III SYSTEM MODEL

A. Load Model

As shown in Fig. 1, the three-phase load voltages in $a-b-c$ coordinates can be written as

$$\begin{bmatrix} V_{la} \\ V_{lb} \\ V_{lc} \end{bmatrix} = R_l \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (1)$$

where balanced three-phase loads are assumed ($R_{la} = R_{lb} =$
$R_{lc} = R_l$ and $L_{la} = L_{lb} = L_{lc} = L_l$). By using the well-known
Park transformation

$$T = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2)$$

Equation (1) can be transformed to the synchronously rotating reference frame as

follows $\begin{bmatrix} V_{ld} \\ V_{lq} \end{bmatrix} = R_l \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + L_l \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}$

Note that $\theta = \tan^{-1}(V_{lq} / V_{ld})$ and V_{l0} is neglected in (3)since the system is assumed to be balanced. Since the angle θ is calibrated by the PLL at each cycle, the error will not be accumulated. When *il* is replaced by the sum of the source current *is* and inverter current *ie*, we have

$$\begin{bmatrix} V_{ld} \\ V_{lq} \end{bmatrix} = R_l \begin{bmatrix} i_{sd} \\ i_{slq} \end{bmatrix} + R_l \begin{bmatrix} i_{ed} \\ i_{eq} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{ed} \\ i_{eq} \end{bmatrix} + L_l \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}$$

$$+ L_l \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + L_l \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} i_{ed} \\ i_{eq} \end{bmatrix} \quad (4)$$

International Journal of Power Control Signal and Computation (IJPCSC)
Vol. 4 No. 2 April- June -2012
©gopalax journals,singapore
ISSN:0976-268X
Available at : http://ijcns.com

B. VSI AC-Side Model

When the load current i_l in Fig. 1 is replaced by $i_s + i_e$, the source voltage V_S and inverter output voltage e can be
Written as

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \frac{a_1}{L_l}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{b_1}{L_l}\frac{d}{dt}\begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{c_1}{L_l}\begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{d_1}{L_l}\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \frac{a_2}{L_l}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{b_2}{L_l}\frac{d}{dt}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{c_2}{L_l}\begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{d_2}{L_l}\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{6}$$

Transforming (5) and (6) to the synchronous reference frame and rearranging, we have

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{ed} \\ i_{eq} \end{bmatrix} = \begin{bmatrix} -\frac{a_2}{b_2} & \omega & -\frac{c_2}{b_2} & 0 \\ -\omega & -\frac{a_2}{b_2} & 0 & -\frac{c_2}{b_2} \\ -\frac{a_1}{b_1} & 0 & -\frac{c_1}{b_1} & \omega \\ 0 & \frac{L_l}{b_1} & 0 & -\frac{d_1}{b_1} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{ed} \\ i_{eq} \end{bmatrix}$$

$$+\begin{bmatrix} -\frac{d_2}{b_2} & \omega & -\frac{L_l}{b_2} & 0 \\ -\omega & -\frac{d_2}{b_2} & 0 & -\frac{L_l}{b_2} \\ -\frac{L_1}{b_1} & 0 & -\frac{d_1}{b_1} & 0 \\ 0 & \frac{L_l}{b_1} & 0 & -\frac{d_1}{b_1} \end{bmatrix}\begin{bmatrix} \sqrt{2}|V_s| \\ 0 \\ ed \\ eq \end{bmatrix}$$

Where $|vs|$ is the rms value of vsa.

C. VSI DC-Side Model

The power balance equation of the VSI dc side and ac side is expressed as [5]

$$V_{dc} i_{dc} = \frac{3}{2}\left(e_d i_{ed} + e_q i_{eq}\right) \tag{8}$$

In addition, the dynamic equation for V_{dc} can be derived from
a current balancing formula as follows:

$$\frac{d}{dt}V_{dc} = -\left(\frac{V_{dc}}{R_{dc}C_{dc}} + \frac{i_{dc}}{C_{dc}}\right) \tag{9}$$

From (8), the current i_{dc} in (9) can be expressed in terms of the state variables V_{dc}, i_{ed}, and i_{eq} as follows:

$$i_{dc} = \frac{3}{2V_{dc}}\left(e_d i_{ed} + e_q i_{eq}\right) \tag{10}$$

IV. DESIGN OF FIXED-GAIN PI CONTROLLER FOR STATCOM

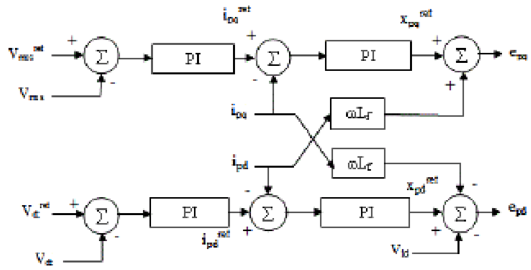

Figure. 2. ***Fixed-gain PI controller for STATCOM***

With the dynamic model for the system at hand, we can proceed to design a fixed-gain PI controller for the STATCOM in order to regulate a load bus voltage under disturbance conditions. Fig. 2 shows the block diagram for the fixed-gain PI controller for the STATCOM.

It is observed from Fig. 2 that the STATCOM controller is composed of four fixed-gain PI controllers: the *d*-axis current regulator, the *q*-axis current regulator, the dc voltage regulator, and the ac voltage regulator. The primary function of the *d*- and *q*-axis current regulators is to regulate the *d*- and *q*-axis inverter currents i_{ed} and i_{eq} to the desired values i^*_{ed} and i^*_{eq} by adjusting the inverter output voltages *ed* and *eq*. The desired MI and angle α can be computed from these inverter output voltages e_d and e_q, as shown in the figure. Note that the *d*-axis is aligned to the load voltage *vl* in the PI controller design process, while the *d*-axis for solving the VSI ac-side equations in (7) is aligned to the source voltage *vs*. As a result, the computed phase angle α must be augmented by the phase angle difference between *vs* and *vl*, i.e., θ, before it is sent to the PWM generator to generate the switching pulses for the inverter switches in order to have correct phases for the inverter output ac voltages e_a, e_b, and e_c. The dc voltage v_{dc} for the dc capacitor is regulated to the desired value $v*_{dc}$ by the dc voltage regulator. On the other hand, the load voltage $|v_l|$ is kept at the desired value $|vl|*$ by the ac voltage regulator. Details on the design of the four regulators have been described in [11]–[12]. It has been found in [11]–[12] that, as far as the dynamic performance for load bus voltage regulation under disturbance conditions is concerned, the controller gains for the ac voltage regulator, i.e., *KP* and *KI* , play a more important role than those for the other three regulators.

As a result, only the design of the controller gains for the ac voltage regulator is discussed in this

International Journal of Power Control Signal and Computation (IJPCSC)
Vol. 4 No. 2 April- June -2012
©gopalax journals,singapore
ISSN:0976-268X
Available at : http://ijcns.com

paper. To determine proper gains for the PI controllers, the nonlinear dynamic equations (12) and (13) for the system are Linearized around a nominal loading condition, and the resulting Linearized state equation is given by

$$\dot{X}(t) = AX(t) + BU(t)$$

where $X(t) = [i_{sd}\ \ i_{sq}\ \ i_{ed}\ \ i_{eq}\ ]^T$ is the state vector and $U(t) = [e_d\ \ \ e_q]^T$ is the control vector. In this paper, heavy load condition is chosen as the nominal operating condition.

V DESIGN OF SELF-TUNING STATCOM CONTROLLER

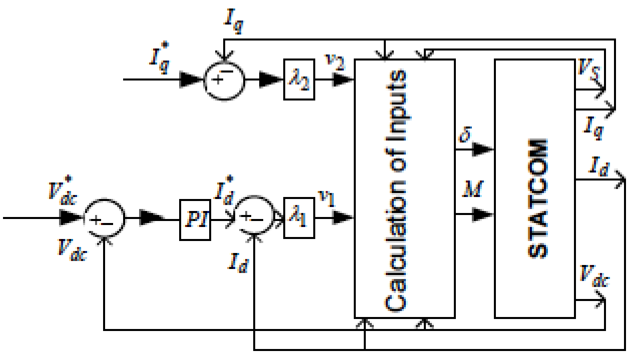

Figure. 3. Block diagram of the proposed PSO self-tuning STATCOM controller.

In the design of the fixed-gain STATCOM controller in the previous section, the PI controller gains *KP* and *KI* have been determined based on a particular loading condition (heavy load condition in this paper), and these gains are fixed in daily operation of the STATCOM. Since these controller gains have been designed to give good dynamic responses for that particular loading condition, it may happen that unsatisfactory responses are observed as load changes with time. Thus, it is desirable to adjust the PI controller gains when there is a significant change in system load. In this paper, the PI controller gains *KP* and *KI* are adjusted by the ANN self-tuning controller as shown in Fig. 4.

VI. PARTICLE SWARM OPTIMIZATION (PSO)

Optimization methods often detect optima in difficult optimization problems faster that traditional methods [22]. One of the most powerful swarm intelligence-based optimization methods, named PSO, was introduced by Kennedy and Eberhart The general principles for the PSO algorithm are stated as follows. Suppose that the search space is n dimensional, and then the i_{th} particle can be represented by a *n*-dimensional vector, $V_i = [v_{i1}, v_{i2}, \ldots, v_{in}]^T$

$X_i = [X_{i1}, X_{i2}, \ldots\ldots, X_{in}]$ and velocity is

$V_i = [V_{i1}, V_{i2}, \ldots\ldots V_{in}]$

Where = 1, 2,..., *N* and *N* is the size of population. In PSO, particle *i* remembers the best position it visited so far, referred to as $P_I = [P_{i1}, p_{i2}, \ldots\ldots P_{in}]^T$ And the best position of the best particle in the swarm is referred as $G = [g_1, g_2, \ldots\ldots g_n\ \ ]^T$ Each particle *i* adjusts its position in next iteration*t+1* Where ω (*t*) is inertia coefficient which gradually decreases from 1 at first iteration to a small magnitude about zero on a straight line. χ is constriction factor which is used to limit velocity. 1 *c* and 2 *c* denote the cognitive and social parameters respectively. *r1* and *r2* random real numbers drawn from uniformly distributed interval [0,1]. The inertia coefficient in (11) is employed to manipulate the impact of the previous history of velocities on the current velocity.

Therefore, ω (*t*) resolves the tradeoff between the global and local exploration ability of the swarm. A large inertia coefficient encourages global exploration while small one promotes local exploration. Experimental results suggest that it is preferable to initialize it to a large value, giving priority to global exploration of search space, and gradually decreasing as to obtain refined solution.

VII. DESIGN OF SELF-TUNING STATCOM CONTROLLER USING PSO

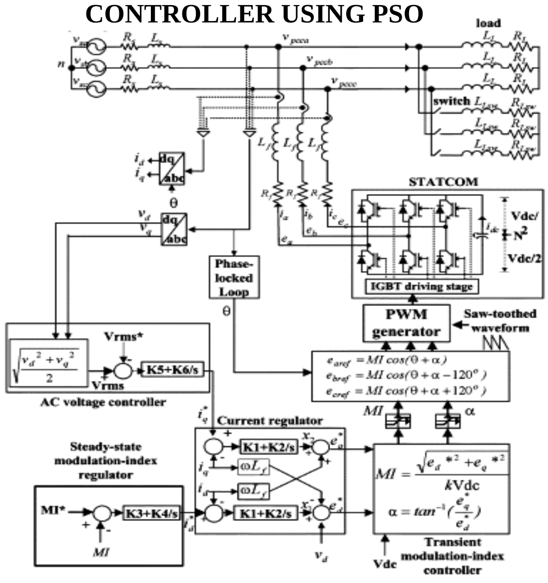

Figure. 5Design of self-tuning statcom controller using pso

International Journal of Power Control Signal and Computation (IJPCSC)
Vol. 4 No. 2 April- June -2012
©gopalax journals,singapore
ISSN:0976-268X
Available at : http://ijcns.com

The procedures followed by the proposed PSO self-tuning STATCOM controller to adjust the PI controller gains are summarized in Fig. 4. Details for these procedures are described as follows.

Determine Stable Regions for PI Controller Gains KP and KI :

In the design of the self-tuning PI controller for the STATCOM, it is essential for the system to remain stable when the PI controller gains are adapted by the PSO algorithm. Therefore, the stable regions for the PI controller gains *KP* and *KI* must be first determined. This is done by computing the Eigen values of the linearized state equation (11) for all possible combinations of *KP* and *KI* . The results are shown in Fig. 5 where the stable regions are depicted for the system with heavy load, medium load, and light load, respectively.

Measure Load Voltage vl and Current il:

The three phase load voltages *vla*(*t*), *vlb*(*t*), and *vlc*(*t*) and currents *ila*(*t*), *ilb*(*t*), and *ilc*(*t*) are measured with a sampling period of 1/15360 s, which is equivalent to 256 samples per cycle for a 60-Hz system. The analog signals fetched by the Hall sensors are first converted to digital signals through a multichannel data acquisition card, as shown in Fig. 1, before they are sent to the digital computer.

Estimate Load Impedance:

To estimate the equivalent load resistance *Rl* and inductance *Ll*, the measured three phase load voltages *vla*(*t*), *vlb*(*t*), and *vlc*(*t*) and currents *ila*(*t*), *ilb*(*t*), and *ilc*(*t*) are first transformed to *d*- and *q*-axis components *vld*, *vlq*, *ild*, and *ilq* using the transformation matrix *T* in (2). Then,the desired values for *Rl* and *Ll* can be derived from (3), andthe results are given as follows:

Check if There Is a Significant Change in R_l and L_{ll}:

When there is no significant change in system load, it is not necessary to update the PI controller gains *KP*desired and *KI*desired. These controller gains are updated when there is a change of more than 1% in system load impedance

$|Z_l| = |R_l + j\omega L_l|$.

Update Kdesired = [KPdesired KIdesired]T using the PSO Algorithm:

When there is a significant change in the system load, the following steps are followed to update the PI controller gains *KP*desired and *KI*desired.

Step 1) Determine initial particle positions *K*(0) *P* , velocities *V* (0) *P* , and weight *w*(0). As shown in Fig. 6, the PSO algorithm begins with the selection of initial positions *K*(0) *P* , initial velocities *V* (0) *P* (*P* = 1, . . . , 10) for the ten particles, and weight *w*(0) =1.5 at iteration 0. In this paper, ten particles were used for each iteration, and a total of 21 iterations were executed by the PSO algorithm. Note that the number of particles and number of iterations were selected such that satisfactory gains could be achieved in a short period. The initial positions (controller gains) *K*(0)*P* = [*K*(0) *PPK*(0) *IP*]T were selected randomly within the stable regions for PI controller gains. On the other hand, the initial velocities (controller gain increments) *V*(0)*P* =[Δ*K*(0)*PP*Δ*K*(0)*IP*]T were selected randomly between −1 and 1.

Step 2) Determine the best particle positions *Pbest* = *KP*(*pbest*) and the best global position *gbest* = *K*(*gbest*) for initial particle positions *K*(0) *P* . The performance of the system with the PI controller gains *KP* and *KI* can be described by the evaluation Function *E* .

Note that the integral of absolute error (IAE) in load bus voltage |*vl*| has been employed as the evaluation function. It has been mentioned that a controller with minimum IAE will result in a response with relatively small overshoot and short rising time. Thus, satisfactory stability, as well as fast response, can be achieved by the proposed controller designed using IAE criterion.

Step 3) Update particle velocities *V*(*i*+1)*P* ,positions *K*(*i*+1)*P* ,and weight *w*(*i*). For a particle *P* at iteration *i* +1, its position *K*(*i*+1)*P* = [*K*(*i*+1)*PPK*(*i*+1)*IP*]T and velocity *V* (*i*+1)
P = [Δ*K* (*i*+1) *PP*Δ*K* (*i*+1) *IP*] T

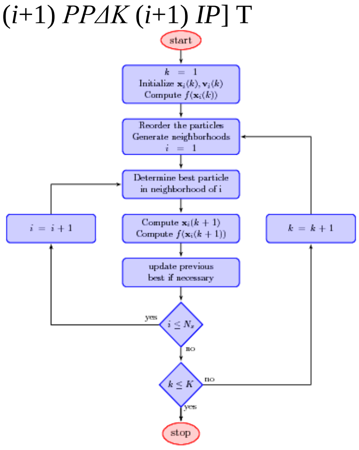

Figure. 7. Flowchart for the procedures of adjusting PI controller gains by the PSO self-tuning STATCOM controller.

IX. CONCLUSIONS

A STATCOM model has been developed with all the necessary components and controllers in order to demonstrate its effectiveness in maintaining simple and fast voltage regulation at any point in the transmission line. The values of the DC link capacitor and battery source were optimized using the PSO and the simulations results were compared with that of the system without compensation and with STATCOM, under both optimized and un-optimized conditions. The comparison of voltage compensation for inductive as well as capacitive load conditions show that the performance of STATCOM tuned with PSO was the best and closest to the nominal value of voltage of 1 per uni

REFERENCES

1. L. Gyugyi, "Dynamic compensation of ac transmission lines by solidstate synchronous voltage sources," *IEEE Trans. On Power Delivery,* vol. 9, No.2, pp 904-911, April 1994
2.]T. An, M.T. Powell, H.L. Thanawala and N. Jenkins, "Assessment of two different STATCOM configurations for FACTS application," in *Power Systems,* Stafford, England, UK: IEEE
3. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators," *Proc. Inst. Elect. Eng. C*, vol. 140, no. 4, pp. 299– 306, Jul. 1993.
4. G. Joos, L. T. Moran, and P. D. Ziogas, "Performance analysis of a PWM inverter VAR compensator," *IEEE Trans. Power Electron.*, vol. 6, no. 3, pp. 380–391, Jul. 1991. 5] B. S. Chen and Y. Y. Hsu, "A minimal harmonic controller for a STATCOM," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 655–664,Feb. 2008.
5. S. Chen and Y. Y. Hsu, "A minimal harmonic controller for a STATCOM," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 655–664,MFeb. 2008.
6. S. Chen and 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, Jan. 2007.
7. T. Chang and Y. Y. Hsu, "Design of an ANN tuned adaptive UPFC supplementary damping controller for power system dynamic performance enhancement," *Electr. Power Syst. Res.*, vol. 66, no. 3, pp. 259–265, Sep. 2003.
8. S. Mohagheghi, Y. del Valle, G. K. Venayagamoorthy, and 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, Feb. 2007.
9. S. Mohagheghi, R. G. Harley, and G. K. Venayagamoorthy, "An adaptive Mamdani fuzzy logic based controller for STATCOM in a multimachine power system," in *Proc. ISAP*, Nov. 2005, pp. 228–233.
10. S. Mohagheghi, G. K. Venayagamoorthy, and R. G. Harley, "Fully evolvable optimal neurofuzzy controller using adaptive critic designs," *IEEE Trans. Fuzzy Syst.*, vol. 16, no. 6, pp. 1450–1461, Dec. 2008. 11] C. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators," *Proc. Inst. Elect. Eng.—C*, vol. 140, no. 4, pp. 299– 306, Jul. 1993.
11. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators," *Proc. Inst. Elect. Eng.—C*, vol. 140, no. 4, pp. 299– 306, Jul. 1993.
12. S. Chen and Y. Y. Hsu, "A minimal harmonic controller for a STATCOM," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 655–664,
13. T. Chang and Y. Y. Hsu, "Design of an ANN tuned adaptive UPFC supplementarydamping controller for power system dynamic performanceenhancement," *Electr. Power Syst. Res.*, vol. 66, no. 3, pp. 259–265,Sep. 2003.. 2008.