VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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A PARTICLE SWARM OPTIMIZED PI CONTROLLERS FOR THE MANAGEMENT OF THE UNIFIED POWER FLOW CONTROLLERS IN A SINGLE MACHINE INFINITE BUSBAR SYSTEM

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ABSTRACT

In this paper is presented the design and simulation based validation of a novel Particle Swarm Optimization (PSO) designed set of PI controllers for the management of the two converters of the Unified Power Flow Controller (UPFC). The performance of the PSO tuned PI controllers are compared against the performance of the PI controllers tuned by the traditional Zeigler Nicholas method. The proposed idea has been implemented in the MATLAB SIMULINK environment and the results of simulation validate the proposed idea.

Keywords: flexible AC transmission system, fuzzy logic controller, proportional integral controller, static synchronous compensator, MATLAB SIMULINK.

1. INTRODUCTION

Unified Power Flow Controllers belong to the family of Flexible AC Control Systems and is an important member in the FACTS family. The UPFC combines the features of the static synchronous compensator (STATCOM) and that of the static synchronous series compensator (SSSC).

While the STATCOM is responsible for the management of reactive power support to the system the SSSC ensures the delivery of required real and reactive power to the load or into the grid to which the SSSC is connected.

Both the STATCOM and the SSSC are basically Voltage Source Converters and are controllable with two degrees of freedom viz. modulation index MI and phase angle δ. using these two parameters as the manipulated variables the two converters STATCOM and SSSC are set to meet the operational requirements.

When there are two manipulated parameters naturally there could be a minimum of two controllers. Therefore in respect of the STATCOM we have a set of two controllers of the PI type and also in the case of the SSSC we have a set of two PI controllers.

In the case of the STATCOM the two PI controllers are meant respectively to maintain the voltage at the point of common coupling and the DC link voltage at the desired level. In the case of the SSSC the two PI controllers are respectively meant to maintain the delivered real and reactive powers at the desired level.

Since both the STATCOM and the SSSC are coupled systems we adopt the synchronous rotating frame technique to arrive at the representative DC signals that correspond to the real and reactive quantities of the voltages and currents and then proceed with the implementation of controllers.

The designs of the PI controllers involve the fairly precise mathematical model of the plants under control and the controllers. The classical methods of analysis of the control system using root locus and other MATLAB supported tools have been used.

In respect of the control schemes for the management of the UPFC a clear literature survey has been carried out and it reveals that there has been a proliferation of control schemes adopted for the control of the UPFC and each method has its own advantages and disadvantages. In [1, 2], the authors discussed the power quality in power systems and FACTS controllers. In [3], the design of a Self-Tuning PI Controller for a STATCOM Using PSO has been proposed. The modelling, control strategy and application of UPFC in interconnected power system has been discussed in [4]. Design of UPFC for power system damping in SMIB has been discussed in [5, 6]. A matrix converter-based UPFC has been proposed in [7]. A dynamic modelling of UPFC by Two shunt voltage-source converters and a series capacitor has been presented in [8]. In [9], transient analysis of a UPFC and its application to design of the dc-link capacitor has been proposed. The application of PSO in designing UPFC has been proposed in [10]. In [11], the authors explained the particle swarm-explosion, stability, and convergence in a multidimensional complex space.

2. GENERAL CONSIDERATIONS

STATCOM and the SSSC are the two converters associated with the UPFC. The structure and location of the STATCOM and the SSSC in the UPFC system will be as shown in Figure-1. These two converters are three phase Graetz bridge converters and share a common a common DC link capacitor of sufficient voltage and capacity rating. The main structure of the STATCOM and SSSC consists of three legs with two MOSFET switches in each leg. The Source Drain junction of the two MOSFETs in each leg is called the node and thus there are three nodes that are connected to the three phase point of common coupling in the case of STATCOM and the grid in the case of the SSSC through a set of series reactors and three phase transformers.

VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

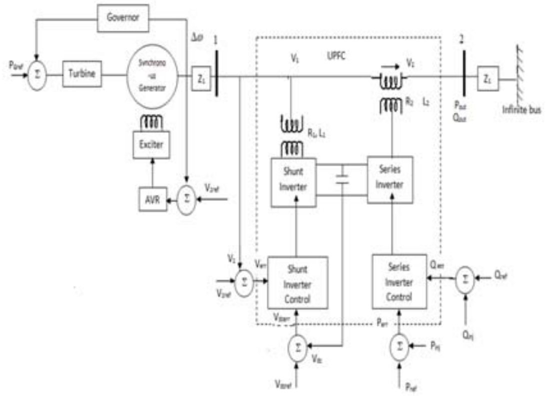

Figure-1. Structure and location of the STATCOM and the SSSC in the UPFC system.

The Pulse Width Modulation (PWM) pulses for the STATCOM and the SSSC can be generated using the Sinusoidal PWM or the Space Vector PWM or with the more recent PWM techniques like the Selective Harmonic Elimination PWM (SHEPWM). In this work the Sinusoidal PWM technique has been adopted. While any of the PWM techniques adopted has its own inherent advantages and disadvantages, it is the reference signal used in the PWM process that dictates the core of the control process that is meant to ensure the control over the flow or power and the maintenance of the required voltage profile at critical points.

The generation of the reference signal is carried out in association with the error in the controlled parameter and the PI controllers in action. The reference signal in a linear balanced three phase PWM will be a set of three sinusoidal signals balanced in phase and amplitude. The amplitude and the phase of the three phase reference signal will control the flow of real and reactive power as presented in the ongoing discussion.

A sinusoidal signal is characterized by its amplitude, phase and frequency. In a line synchronized PWM system the frequency of the reference signal will be same as that of the line to which the converters will be synchronized. Usually there is no control system used for maintain the frequency of the reference signal except a phase locked loop.

The phase of the reference signal and its amplitude will be governed by the control system dynamically.

A. Synchronous reference frame

The controlled parameters of both the converters are generally sinusoidal quantities. In order that an effective control technique is employed the time varying quantities are to be converted into time invariant quantities. For this purpose the Park transformation scheme is used.

The STATCOM is meant to supplement the reactive power demand of the grid and for this purpose the STATCOM controls the voltage at the point of common coupling. The voltage at the point of common coupling [Va Vb Vc] is therefore transformed into [V_d V_q V_0]. The transformation matrix is given in Equation (1).

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (1)$$

After the Park transformation the time invariant d and q quantities of the voltage at the point of common coupling are compared against the set points in the synchronous d and q frame and the errors obtained thereof are taken over respectively to a set of two PI controllers. The output of the PI controller that handles the d component is used as the suggested modulation index and the output of the second controllers is used as the angle of the reference signal. The control scheme is as shown in Figure-2.

In practice one of the PI controllers are used to regulate the Vq quantity of the voltage at the point of common coupling. The other controller is used to maintain the DC link voltage. Therefore the first PI controller contributes for the magnitude of the reference signal that takes care of the voltage at the point of common coupling and the second controller contributes the phase angle theta of the reference signal that takes care of the DC link voltage.

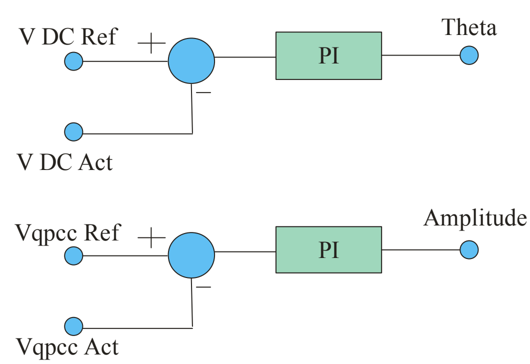

Figure-2. The PI controller based real and reactive power controllers.

Similarly the SSSC also needs a set of two controllers. The first one takes care of the d component of the current entering the grid and the second controller takes care of the q component of the current entering the grid. Both the d and the q components of the current entering into the grid, Id and Iq are compared against preset values of Idref and Iqref voltage at the grid terminals.

The control scheme for the SSSC using PI controllers is shown in Figure-3.

VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
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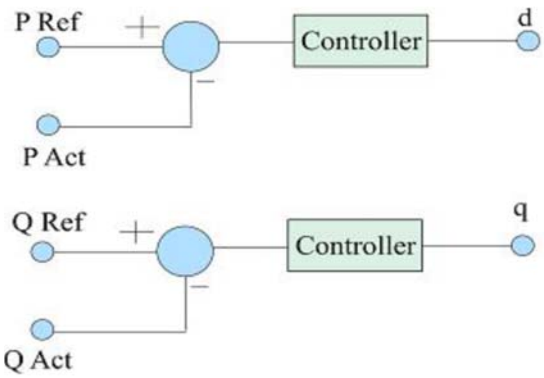

Figure-3. The PI controller based real and reactive power controllers.

B. Review of Particle Swarm Optimization

The PSO is a search algorithm that exploits the intelligence of swarms of birds or schools of fish. The members of such groups are generally known as particles. In the movement of the particles certain characteristic social behaviour are observed and the PSO algorithm is inspired by these behaviour of the swarm.

The function of the PSO algorithm can be summarized as follows.

a. Each particle or member of the society or swarm, has a position in the multi dimensional space and the position of each member is given by P[i j k…..n]. The position of a particle is therefore a vector.

b. Each particle therefore has a displacement between every other particle in the swarm.

c. The goal to be achieved is a certain point in the n dimensional search space that complies with certain conditions.

d. Every particle, in each step of evolution tries to move towards the goal by altering its coordinates in each iteration.

e. The coordinates of each particle is altered by adding an n dimensional displacement, usually known as a velocity, to the present coordinates of each of the particle.

f. While the coordinates of the final goal is not known ahead of time, the closeness of each particle to the final goal is measured in terms of the results obtained by substituting the co ordinates of each particle in an n dimensional function known as the objective function.

g. After altering the coordinates of each of the particle in each iteration, the coordinates of each particle are substituted in the objective function and the error between the actual objective and that obtained by each of the particle are found.

h. Some of the particles may be closer to the final goal while some may be far off. That particle that offers the best result in terms of minimal error is known as the best particle and its current position is the globally best position as a result of the just completed iteration.

i. In the course of iterations going on, with the coordinates of every particle altered in every iteration, there are chances that every particle may come closer to the objective function in some iteration s and move away in some other iteration. Therefore when the results of the past iterations of a certain particle is considered there could be some best states in the past as for that particle is concerned and this position is called the personal best position.

j. The position of the globally best particle in the present iteration and that of the personal best position from the history of iterations the position of each particle is adjusted.

k. Since the direction of the final goal is not known two random factors are included, each one, with the correction corresponding to the global best particle and with the correction corresponding to the personal best position.

l. At the end of the process all the particles end up with almost the same position vector with errors within the tolerable limits and the position of each particle now is the position of the goal and thus the particular point that complies with the conditions set forth in the objective function is identified.

Going by an example, let us consider the estimation of the solution of the given set of simultaneous equations.

$2x + 3y = 14$
$4x + 2y = 11$

In order that a search algorithm is employed for finding the solution vector that complies with the given two equations an objective function is to be formulated. The common objective function for this application is as follows.

(2x + 3y -14)^2 +(4x + 2y -11)^2 = 0.

In this application there is an unique vector [x y] that will satisfy the given objective function.

A PSO algorithm can be used to estimate the values of the elements of the solution vector [x y]. To start with let there be p number of particles. Each of the particle is characterized by is position vector of two elements [x y]. To start with let the position vector of each particle be initialized randomly. If the position vector of each particle is substituted in the objective function then each particle will show up its closeness to the final destination in terms of error in the objective function. Now the position vector of each particle is altered according to the considerations of global best and personal best coordinates also in association with some random variables. Finally the position vector of all the particles will move towards the [4.25 0.625] position that satisfies the objective function.

1) PSO applied to tuning of the PI controllers

Tuning of the PI controller is to find the constants Kp and Ki of the proportional and integral blocks of the PI controller such that the control system satisfies one or more of the desired performance indices. For example a control system may be optimized with appropriate values for Kp and Ki such that the Integral Square Error is minimum.

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

An objective function is therefore to be coined as a function of the variables Kp and Ki. When the right values of Kp and Ki are selected the objective function is achieved.

$$ISE = \int_{0}^{T} [e(t)]^2 \, dt \tag{2}$$

$$e(t) = r(t) - y(t)$$

$$where,$$

$$r(t) = reference\,value$$

$$y(t) = actual\,value$$

C. Review of the structure and control of the STATCOM

Figure-4 shows the structure of the STATCOM and it is a three phase Graetz Bridge arrangement with a DC link capacitor on the DC terminals and a three phase reactor on the AC side. In the context of an UPFC the STATCOM has two distinct purposes. A. To draw the required real power from the three phase line to charge the DC link capacitor and maintain the DC potential across the DC link capacitor at the prescribed level. B. To pump into the grid, at the point of common coupling, the required reactive power and thus to relieve the single machine side from the burden of reactive power and thus further to maintain the voltage at the point of common coupling at the required level.

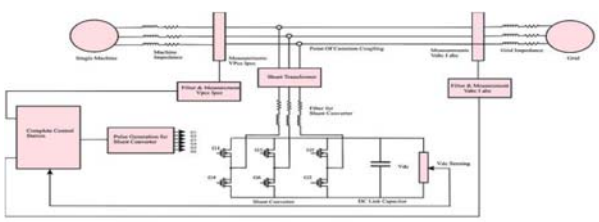

Figure-4. Structure of the STATCOM.

From the basic principles the reactive power transacted across the reactor connecting two terminals 1 and 2 with voltage sources v1 and v2 is given by the relationship

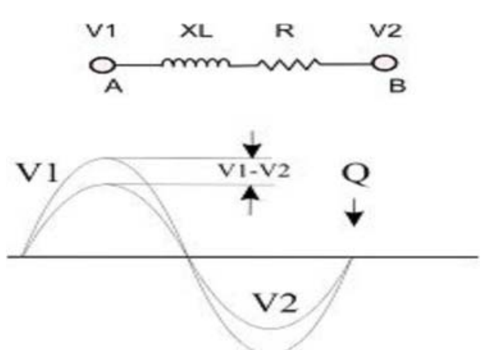

Figure-5. Reactive power transaction.

The equations describing the reactive power flow is shown in Equation (3).

$$Q = \left(\frac{V_1(V_1 - V_2)}{X}\right)\cos\delta \tag{3}$$

If the angle between the two voltages v1 and v2 is zero, Cos 0 being 1 the reactive power flow is solely decided by the difference in the voltage levels v1 and v2. Should v1 is the voltage at the point of common coupling Vpcc and v2 is the voltage at the terminals of the STATCOM converter Vinv if Vinv is raised above Vpcc then reactive power flow will happen through the reactor towards the point of common coupling from the STATCOM terminals and viz.

The real power transacted between two voltage sources v1 and v2 connected through a reactor is given is given by Equation (4)

$$P = \frac{V_1 V_2 \sin\delta}{X} \tag{4}$$

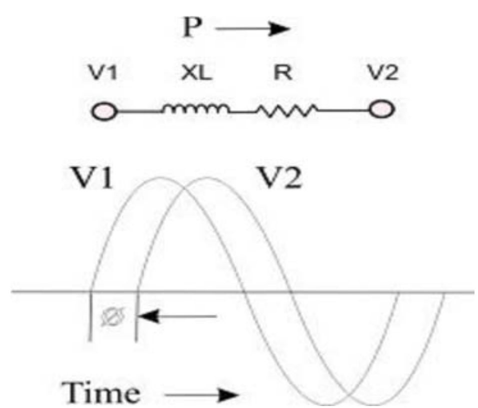

Figure-6. Real power transaction.

This relationship implies that irrespective of the voltages v1 and v2 with zero phase difference between v1 and v2 the real power transacted will be zero. It is therefore the phase angle δ that decides the magnitude and direction of real power flow between terminals v1 and v2.

The STATCOM being the controllable equipment, we can control the magnitude and direction of the real and reactive power flow between the terminals 1 and 2 by changing accordingly the phase angle and modulation index of the reference signal used to generate the PWM pulses for switching the power switches of the STATCOM.

There are two controllers associated with the STATCOM. The first controller takes care of the reactive power demand of the load and in this case the manipulated parameter will be the modulation index used for the converter. The second controller takes care of the DC link voltage. If there is a fall in the DC link voltage the STATCOM draws the required real power from the PCC and tops up the DC link capacitor. If the Dc link voltage

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increases beyond the set value the STATCOM drives some real power into the PCC and thus pulls down the DC link voltage to the required level. In this case the manipulated variable is the angle δ of the reference signal used in the PWM section of the STATCOM.

1) Review of the Structure and Control of the Static Series Synchronous Compensator (SSSC)

The second element of the UPFC is the SSSC. The SSSC consists of a three phase Graetz Bridge converter and the output of this converter comes in series with the load through a series insertion transformer as shown in Figure-7. As for the voltage that is being series inserted, Vse, there are two degrees of freedom. Both the amplitude and the phase angle of this voltage Vse can be altered. The series inserted voltage Vse comes in series with the source voltage Vs and the load voltage Vl becomes Vl = Vs +Vse.With the source voltage Vs as the reference the resultant voltage available for the load is given by the locus of the series inserted voltage Vse with constant amplitude and the angle δ varied from 0 towards 360.

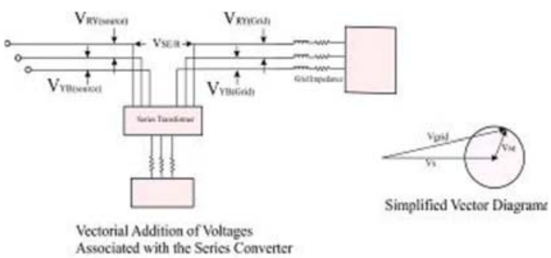

Figure-7. Static Series Synchronous Compensator (SSSC).

The purpose of the SSSC is to ensure that the load terminals are maintained at the required voltage level. If the load terminals are maintained at the required voltage level the load can deliver the required reactive and real power.

Therefore in the control scheme either the decoupled load side voltages Vd, Vqor the real and reactive powers P and Q delivered to load can be used as the controlled parameters. The reactive power injected into the load can be controlled by the modulation index of the reference signal used for PWM by the SSSC and the real power injected into the load can be controlled by controlling the phase angle δ of the reference signal used for PWM by the SSSC.

D. The control systems

In essence there are four controllers viz. two for the STATCOM and two for the SSSC. In this work for all the four controllers empirically tuned PI controllers are first tried and then the four controllers are tuned with a Particle Swarm Optimization (PSO) tuning tool.

Tuning the controller for the DC link voltage of the STATCOM is discussed in detail. However the same procedure has been adopted for all other controllers and the relevant results are recorded and discussed in the results section. The step response, the Bode plot, the Root Locus and the Nyquist plots are compared for the Zeigler Nicholas tuned and the PSO tuned PI controller for the DC link voltage controller section of the STATCOM.

1) PI Controller

In general, in any closed loop system the error is the input to the controller. The controller in due course tries to make the error, it's input, equal to zero. In a typical PI controller the error detected at the input of the PI controller is passed through two processes namely a multiplication process and an integration process separately don on the error and then the results of multiplication and integration are added and the final result is the correction signal. This correction signal when applied to the actuator pushes the output of the plant equal to the set value and eventually the error becomes zero.

Now the tuning of the PI controller is actually finding the correct values of the constant of multiplication or gain known as Kp in the multiplier section and the time constant in the integrator section Ki. The convergence characteristics of the plant output with respect to the set point depend upon the values of Kp and Ki.

a) Zeigler Nicholas tuning procedure

The Zeigler Nicholas tuning procedure as applied to the DC link voltage control is illustrated. The figure shows the location of the PI controller in the control chain. The error between the Vdc_ref and Vdc_act is found and then applied to the PI controller. The output of the PI controller gives the phase angle δ and this δ is manipulated to finally settle down at a certain value to make the error Vdc_ref - Vdc_act equal to zero.

As discussed earlier the DC link voltage is a function of the phase angle δ and the phase angle δ can be changed from -1.57 to 1.57. With the capacitor at the DC link initially discharged is suddenly charged by giving a value for δ as 1.57. While keeping the modulation index at 1. This action charges the capacitor and the voltage across the DC link capacitor rises in a fashion as shown in Figure-8. The curve depicted in figure 8 is known as the reaction curve.

The reaction curve has a convexity, and concavity and a point of inflexion and through the point of inflexion a tangent is drawn to the reaction curve that intersects the time axis at point A and the steady state lie at point B. After projecting point B onto the x axis we have two distances L and T as shown in the Figure-8.

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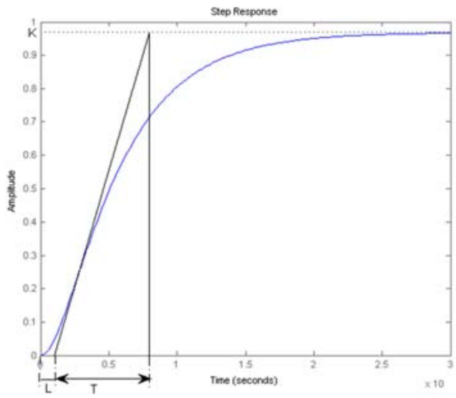

Figure-8. ZN reaction curve for PI controller 1.

With the two values of L and T the Kp and Ki values are found from the empirical formulae as put forth from the Zeigler Nicholas method as,
Kp = 0.9(T/L) and Ki = 0.27(T/L^2).

Theclosed loop form is completed with the PI controller in place with the Kp and Ki values as found using the Zeigler Nicholas method.

Table-1. ZN values for PI controller 1.

T	L	Kp	Ki
6.93	1.18	5.2855	1.3437

The entire simulation has been carried out in the MATLAB / SIMULINK platform.

b) Particle Swarm Optimization (PSO)

Optimization is the technique of finding out the most optimal values of that set of variables governing the performance of a system with an objective that guarantees the best state of the objective of the system. Simply stated the KP and Ki values of a PI controller determine the performance of the PI controller. Minimizing the overshot, minimizing the transient period, minimizing the steady state error are some of the requirements of a good control system. However minimizing the Integrated Square Error is usually the predominant objective of most control systems.

So also in this research finding the values of Kp and Ki that will minimize the Integrated Square Error is the prime objective.

After knowing the objective and after identifying the variables that will influence the objective the next requirement is the suitable algorithm for optimization. While we have a number of optimization techniques available the PSO is selected here because of its less complexity and speed as compared to other contemporary search algorithms.

The PSO algorithm starts up with a number of N candidates. Each of the N candidates are initialized with a set of random values for Kp and Ki. Thus candidate 1 is initialized with Kp_1, Ki_1 and so on up to Kp_N and KI_N for the N^{th} candidate. The candidates are also known as particles and each particle can be viewed as the member of a flock of birds or a school of fish since the very essence of the PSO has been inspired after observing the behavior of flocks of birds or schools of fish.

If it is assumed that a plant with an initial steady state at it's output is disturbed by assigning a new set value for the output, an error is first created and this error after passing through the controller activates the plant and the output of the plant changes continuously until the set value is reached at the output.

During the course of the transient, depending upon the order of the system under control the out may exhibit overshoot oscillations etc. and finally the steady state may be reached. At any instant before reaching the steady state the output exhibits an error with respect to the set value and this error is squared and integrated to give a quantity called the Integrated Square Error (ISE). The ISE can be minimum only if the transient process is optimal with minimal overshoot, and oscillations. Now the objective function to be adopted by the PSO is the function that relates the ISE and the Kp and Ki values. The purpose of the PSO is to find out the most suitable values for Kp and Ki such that the ISE is minimum.

After initializing the Kp and Ki values for each of the particles candidates the performance of each set of Kp and Ki are measured and the values of the Kp and Ki for each of the candidate particles are altered in such a manner that after a number of iterations the Kp and Ki values of each particle becomes correspondingly equal and also for this unique set of K[and Ki values the objective function is also at its minimal value.

Consider a particular candidate particle, at the end of the k^{th} iteration its Kp and Ki values are say x and y. After the K^{th}iteration its performance is compared against its past performances and the performance of other candidates in the K^{th} iteration. In the past iterations the particle under consideration might have exhibited the best performance in a particular iteration called the personal best performance. In the Kth iteration there could be the best of the particles exhibiting the best performance amongst all particles and this particle is said to be the globally best performing particle. After each iteration the Kp and Ki values of each particle will be modified by a factor called velocity. The velocity added to each particle is a function of the past best performance of the particle from among the past iterations and the globally best of the particles from the just completed iteration.

The velocity added to any particle is given by the relationship given in equation 5.

$$v = \omega + c_1 * r_1(pbest - x) + c_2 * r_2(gbest - x) \quad (5)$$

Two random factors c1 and c2 are also included in the calculation of the velocity to be imparted to every candidate.

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Table-2. PSO parameters.

Parameter	Value
Population size	50
Number of generations	200
C1, constant representing cognitive component	2
C2, constant representing social component	2
Random numbers r1, r2	[0,1]
Inertia constant	Decreasing from 0.9 to 0.4

3.MATLAB / SIMULINK SIMULATION

Figure-9 shows the complete UPFC system with the source and the grid. The system parameters are:
Nominal Source Voltage (Line) 33KV.
Nominal Source short circuit capacity 100e6 VA.
System frequency 50Hz.
Nominal Grid Voltage (Line) 33KV.
Nominal Load P = 20e6 W and Q = 20e6 VAR.
DC link Voltage 66KV
STATCOM capacity 50e6 VA.
SSSC capacity 50e6 VA.

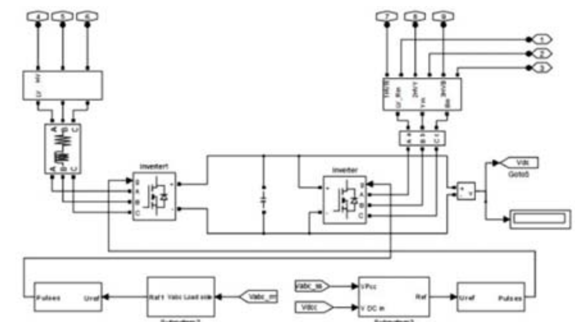

Figure-9. UPFCMATLABsimulink model.

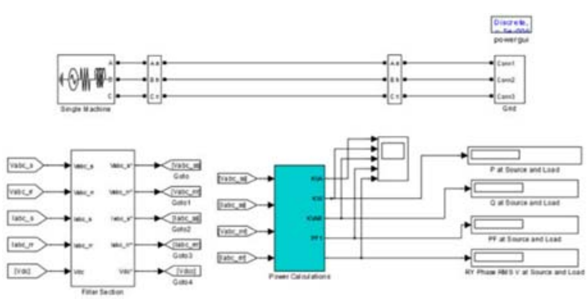

Figure-10. 3 Phase single machine infinite bus bar.

4. RESULTS AND DISCUSSIONS

An UPFC has been simulated in MATLAB SIMULINK environment with the four controllers, two each for the STATCOM and the SSSC respectively. These controllers are of the PI type. These PI controllers were tuned by the Zeigler Nicholas method and the PSO based tuning method. The performance of the UPFC in both the cases were recorded and presented herein. Figures 11 and 12 give the results of simulation with Zeigler Nicholas method of tuning the PI controllers. Figures 13 and 14 correspond to the results with PSO based tuning of the PI controllers.

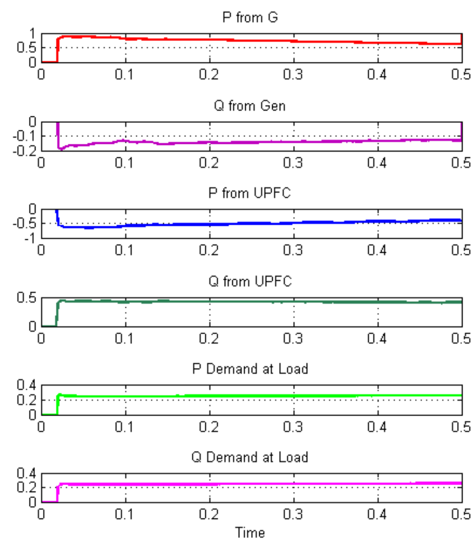

Figure-11. P and Q values- ZN tuning.

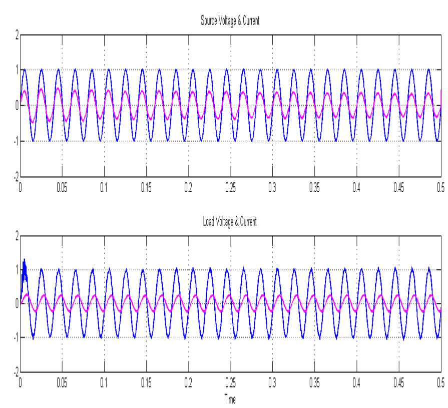

Figure-12. Source and load voltage and current- ZN tuning.

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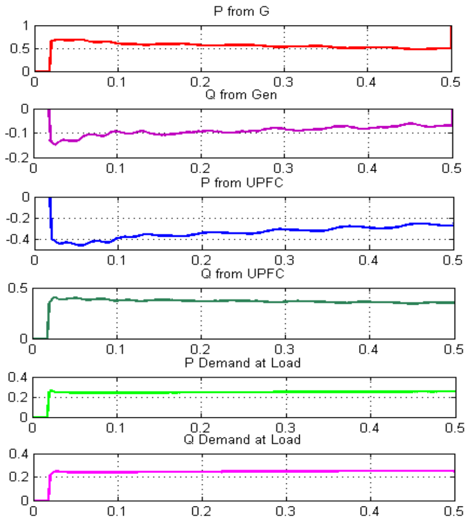


Figure-13. P and Q values- PSO tuning.

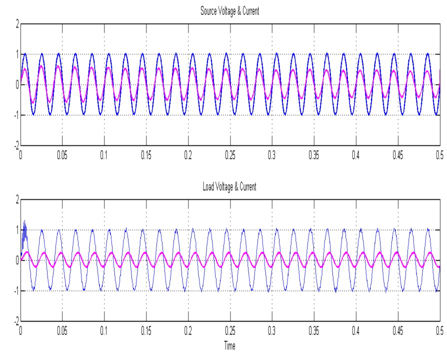


Figure-14. Source and Load voltage and current-PSO tuning.

Table-3 gives a comparison of the integrated square error for the normalized DC link voltage controller. It is evident from Table-3 that the integrated square error is reduced to about 1/3rd of that observed for the ZN tuned PI controller case.

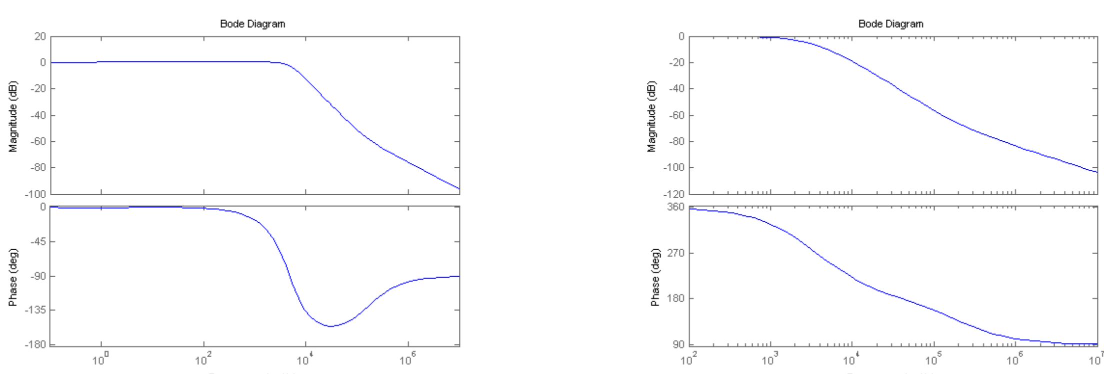
Table-3. ISE values for ZN and PSO algorithm.

Algorithm	Generations	Results			
		Best value	Worst value	Mean value	Standard deviation
ZN	-	0.8965	-	-	-
PSO	200	0.2985	0.5704	0.4216	0.0087

Table-4 gives the Kp and Ki values for the all the four controllers as derived by the ZN methods of tuning and the PSO method of tuning. A comparison of thebodeplot for the DC link voltage control loop is given in Figure-15.

Table-4. PI (Kp and Ki) values for ZN and PSO algorithm.

	PI1		PI2		PI3		PI4	
	Kp1	Ki1	Kp2	Ki2	Kp3	Ki3	Kp4	Ki4
ZN	5.28	1.34	4.18	1.1	5.17	1.27	5.58	1.98
PSO	4.24	0.89	2.47	0.3	1.37	1.34	1.68	0.75



(a) (b)

Figure-15. Bode Plot for the DC link voltage control loop (a). ZN based tuning (b).PSO based tuning.

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With reference to the bode plot it is clear that the magnitude curve is more smooth in the case of the PSO-PI tuned controller than the ZN tuned controller and that more gain margin is available in the case of the PSO tuned PI controller for the DC link voltage controller.

5. CONCLUSIONS

In this work, two possibilities of tuning the four controllers of the UPFC have been carried out. The results obtained reveal that the performance of the controllers that used the PSO methodology of tuning are promising than those adopted the Zeigler Nichols method of tuning.

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