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Artificial Immune System Based DSTATCOM Control for an Electric Ship Power System

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Abstract— **Distribution Static Compensator (DSTATCOM) is a shunt compensation device which is generally used to solve power quality problems in distribution systems. In an all-electric ship power system, these power quality problems mainly arise due to the pulsed loads, which causes the degradation of the entire system performance. This paper presents the application of DSTATCOM to improve the power quality in a ship power system during and after pulsed loads. The control strategy of the DSTATCOM plays an important role in maintaining the voltage at the point of common coupling. A novel adaptive control strategy for the DSTATCOM based on artificial immune system (AIS) is proposed. The optimal parameters of the controller are first found using particle swarm optimization. This provides a sort of innate immunity to common system disturbances. For unusual system disturbances, these optimal parameters are modified online, thus providing adaptive immunity in the control system. To evaluate the performance of the DSTATCOM and the AIS adaptive controller, a ship power system is developed in the MATLAB/SIMULINK environment. The effectiveness of the DSTATCOM and the AIS controller is examined for pulsed loads of different magnitudes and durations.**

I. INTRODUCTION

The power system of an all-electric navy ship has an integrated network, where the propulsion load, the distribution loads, sensor and other emergency loads and pulse loads (rail guns, aircraft launchers etc.) – all are part of the same electrical network. Among the loads, the effects of pulsed loads are most detrimental for the power quality of ship power distribution system as the pulsed loads require a very high amount of power for a very short period of time [1]. In order to improve the survivability of a navy ship in battle condition, DSTATCOM or Distribution Static Compensator can be used, which reduces the impact of pulsed loads on the bus voltage and thus keeps the bus voltage at desired level. DSTATCOM is a voltage-source inverter (VSI) based shunt device [2] generally used in distribution system to improve power quality. The main advantage of DSTATCOM is that, it has a very sophisticated power electronics based control which can efficiently regulate the current injection into the distribution bus. The second advantage is that, it has multifarious applications, e.g. a) canceling the effect of poor load power factor, b) suppressing the effect of harmonic content in load currents, c) regulating the voltage of distribution bus against sag/swell etc., d)

compensating the reactive power requirement of the load and so on [3].

The performance of the DSTATCOM is very much dependent on the DSTATCOM controller. Several investigations are being carried out on the control strategies of DSTATCOM which primarily depend on its topology and the type of application. For example, papers [2] and [4]-[6] present different control strategies based on the respective multi-level inverter topologies of shunt compensators. Attempts have been made to make the controller robust by applying sliding mode control strategy as in [7] and [8]. But, all the above control strategies are not adaptive to the system dynamics and hence the performance may not be satisfactory in case of unexpected drastic system disturbances. Also, most of the conventional control schemes of DSTATCOM have several PI controllers. The tuning of PI controllers is a complex task for a nonlinear system. In order to overcome these problems, Computational Intelligence (CI) techniques can be used. There are not so many attempts of using CI techniques in DSTATCOM control. References [9] and [10] are based on Artificial Neural Networks (ANNs). In [9], the PI controllers are replaced by an ANN which is trained using a backpropagation algorithm. But, the training is carried out offline and hence the ANN based controller is not adaptive. In [10], an ANN based reference current generator is used, which is a partially adaptive control strategy. Here, though the reference generator adapts its ANN weights online, but the DC voltage regulation is handled by conventional PI controllers.

This paper presents the application of DSTATCOM to improve the power quality in a ship power system during and after pulsed loads. In addition, a novel adaptive control strategy for a DSTATCOM based on Artificial Immune System (AIS) is proposed. Most of the CI techniques are offline and require prior knowledge of the system behavior. But AIS, which is inspired by theoretical immunology and observed immune functions, principles and models, has the potential for online adaptive system identification and control [11]. Abnormal changes in the system response are identified and acted upon without having any prior knowledge [12]. The AIS DSTATCOM controller exhibits innate and adaptive immune system behaviors.

The rest of the paper is organized as follows: Section II describes the DSTATCOM control scheme adopted in this paper. Section III presents a brief description of Particle Swarm Optimization (PSO) based tuning of the DSTATCOM controller. Section IV explains the

biological immune system and the method of designing an adaptive controller based on the immune system. Section V presents the test ship power system and Section VI demonstrates the results obtained in simulation of the test system and explains the effectiveness of the AIS based controller. Finally, the conclusions are drawn in section VII.

II. DSTATCOM AND ITS CONTROL STRUCTURE

The simplest structure of a DSTATCOM is shown in Fig. 1. The principle of operation of DSTATCOM is based on the fact that the real and reactive power can be adjusted by adjusting the voltage magnitude of the inverter (V_C) and the angle difference between the bus and the inverter output (α). The equations for active and reactive power are:

$$P = \frac{V_{PCC} V_C \sin\alpha}{X} \quad (1)$$

$$Q = \frac{V_{PCC}(V_{PCC} - V_c \cos\alpha)}{X} \quad (2)$$

Where

P = Active Power,
Q = Reactive Power,
V_C = Inverter voltage,
V_{PCC} = Voltage at the Point of Common Coupling,
α = Angle of V_{PCC} with respect to V_C,
X = Reactance of the branch and the transformer.

In steady state operation, the angle α is very close to zero. Now, if $V_{PCC} < V_C$, reactive power flows from the DSTATCOM to the bus. So, by controlling the inverter voltage magnitude V_C, the reactive power flow from the DSTATCOM can be regulated. This can be done in several ways. In this paper, a GTO based square wave Voltage Source Converter (VSC) is used to generate the alternating voltage from the DC bus. In this type of inverters, the fundamental component of the inverter output voltage is proportional to the DC bus voltage. So, the control objective is to regulate V_{DC} as per requirement. Also, the phase angle should be maintained so that the AC generated voltage is in phase with the bus voltage. The schematic diagram of the control circuit is shown in Fig. 2.

Here, the PLL synchronizes the GTO pulses to the system voltage and generates a reference angle. This reference angle is used to calculate positive sequence component of the DSTATCOM current using a-b-c to d-q-0 transformation. The voltage regulator block calculates the difference between reference voltage and measured bus voltage and the output is passed through a PI controller to generate the reactive current reference I_{q_ref}. This I_{q_ref} is then passed through a current regulator block to generate the angle α. This current regulator block also consists of a PI controller to keep the angle α close to zero.
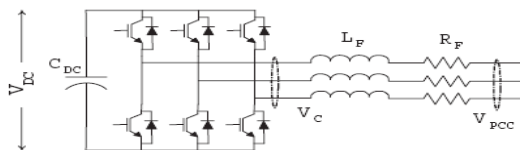

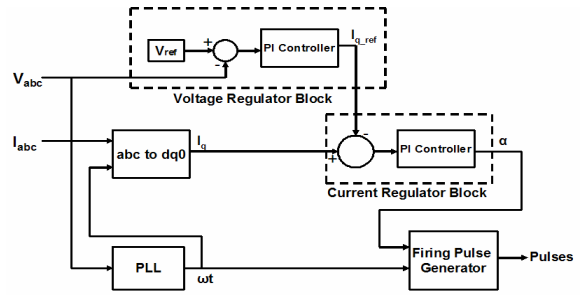Figure 1. Schematic diagram of DSTATCOM

Figure 2. Control Structure for the DSTATCOM

The Firing Pulse Generator block generates square pulses for the inverter from the output of the PLL and the current regulator block. If due to the application of a pulsed load the bus voltage reduces to some extent, the voltage regulator changes the I_{q_ref} and as a result the current regulator increases the angle α so that more active power flows from bus to the DSTATCOM and energizes the capacitor. So the DC voltage increases and consequently the AC output of the inverter also increases and the necessary reactive power flows from DSTATCOM to the bus.

III. PSO BASED TUNING OF DSTATCOM CONTROLLER

Particle swarm optimization is a population based search algorithm modeled after the motion of flock of birds and school of fish [8], [9]. A swarm is considered to be a collection of particles, where each particle represents a potential solution to a given problem. The particle changes its position within the swarm based on the experience and knowledge of its neighbors. Basically it 'flies' over the search space to find out the optimal solution [10].

Initially a population of random solutions is considered. A random velocity is also assigned to each particle with which they start flying within the search space. Also, each particle has a memory which keeps track of its previous best position and the corresponding fitness. This previous best value is called the 'p_{best}' of a particle. The best of all the 'p_{best}' values is called 'g_{best}', of the swarm. The fundamental concept of PSO technique is that the particles always accelerate towards their 'p_{best}' and 'g_{best}' positions at each search instant k. Fig. 3 demonstrates the concept of PSO, where

a) $x_{id}(k)$ is the current position of ith particle with d dimensions at instant k.
b) $x_{id}(k+1)$ is the position of ith particle with d dimensions at instant $(k+1)$.
c) $v_{id}(k)$ is the initial velocity of the ith particle with d dimensions at instant k.
d) $v_{id}(k+1)$ is the initial velocity of the ith particle with d dimensions at instant $(k+1)$.
e) w is the inertia weight which stands for the tendency of the particle to maintain its previous position.
f) c_1 is the cognitive acceleration constant, which stands for the particles' tendency to move towards its 'p_{best}' position.
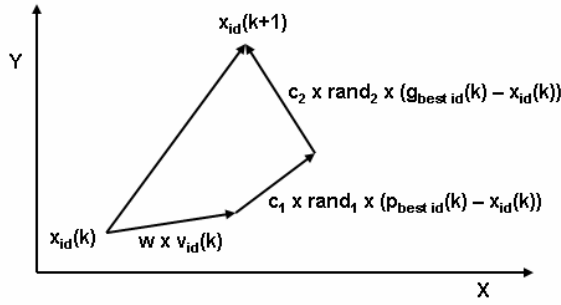
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Figure 3. Concept of changing a particle's position in two dimensions

g) c_2 is the social acceleration constant which represents the tendency of the particle to move towards the 'g_{best}' position.

The velocity and the position of a particle are updated according to the following equations. The velocity of the ith particle of d dimension is given by:

$$v_{id}(k+1) = w \cdot v_{id}(k) + c_1 \cdot rand_1 \cdot (p_{best\_id}(k) - x_{id}(k)) + c_2 \cdot rand_2 \cdot (g_{best\_id}(k) - x_{id}(k)) \quad (3)$$

The position vector of the ith particle of d dimension is updated as follows:

$$x_{id}(k+1) = x_{id}(k) + v_{id}(k+1) \quad (4)$$

Now, in order to find out the optimum DSTATCOM controller parameters with the help of PSO, the four parameters (Kpv = proportional gain of the voltage regulator block, Kiv = integral gain of the voltage regulator block, Kpc = proportional gain of the current regulator block and Kic = integral gain of the current regulator block) are considered to be the four dimensions of each particle of the swarm. Here, bus voltage regulation is one of the main objectives of the DSTATCOM. Hence the cost function is considered in such a way that it minimizes the area swept out by the bus voltage curve above and below the steady state value of the bus voltage during and after the pulsed load application. The mathematical expression for the cost function is as follows:

$$J = \sum_{j=1}^{N} \sum_{t=t_0}^{T} \frac{1}{2} \cdot (|\Delta v(t)| + |\Delta v(t-1)|) \cdot \Delta t \quad (5)$$

Where

J = Cost function
N = No. of operating points
t = time
t_0 = start time for area calculation
T = stop time for area calculation
$|\Delta v(t)|$ = modulus of bus voltage deviation at a particular time instant
$|\Delta v(t-1)|$ = modulus of bus voltage deviation at the previous time instant
Δt = time step.

To find out a near optimal value of the control parameters, the simulation is carried out for three different operating conditions. To have a fast PSO search performance, the values of w, c_1 and c_2 are kept fixed at

0.8, 2.0 and 2.0 respectively and the number of particles taken is 25. The optimum PI controller parameters found by PSO are:

Kpv = 20.0,
Kiv = 1462.5,
Kpc = 20.2,
Kic = 35.1.

IV. BIOLOGICAL IMMUNE SYSTEM AND ADAPTIVE CONTROLLER DESIGN

The natural immune system of a human body is basically the interaction of various cells. Among these, T and B cells play the most vital roles. B cells secrete antibodies, whereas, T cells are made of three types of cells: a) helper T cells, b) suppressor T cells, c) killer T cells. Within the immune system, there is a feedback mechanism. When a non-self cell (antigen) is identified in a human body by APC (Antigen Presenting Cell), it activates helper T cells. Those helper T cells then stimulate the B cells, the killer T cells and the suppressor T cells. Activation of B cell is the most important feedback mechanism of the immune system and it is basically responsible for elimination of antigens. Again, when the number of antigens is reduced, the suppressor T cells inhibit the activities of all other cells. As a result of this inhibitive feedback mechanism, the action of immune system is tranquilized [11].

In this paper, to adapt the four PI controller parameters, which are already found by PSO, the approach described below is followed.

The amount of foreign material (antigen) at k^{th} generation is defined here as the deviation in the bus voltage $\Delta V_b(k)$. The output from the helper T cells stimulated by the antigen is given by

$$TH(k) = m\Delta V_b(k) \quad (6)$$

Where 'm' is the stimulation factor whose sign is positive. The suppressor T cells inhibit the other cell activities and its effect can be represented by

$$TS(k) = m' f\left(\frac{\Delta V_b(k)}{\Delta V_b(k-1)}\right) \Delta V_b(k) \quad (7)$$

Where m' is positive suppression factor. $f(x)$ is a non-linear function which is defined as

$$f(x) = \exp(-x^2) \quad (8)$$

The output of the function is limited within the interval [0, 1]. The total stimulation received by the B cells is based on immune based feedback law which is given by

$$B(k) = TH(k) - TS(k)$$
$$B(k) = \left[m - m' f\left(\frac{\Delta V_b(k)}{\Delta V_b(k-1)}\right)\right] \Delta V_b(k) \quad (9)$$

So, the mechanism basically consists of two actions: once the antigens are found, the TH cells work to eliminate them, whereas the TS cells work to inhibit the actions of other cells. Fig. 4 illustrates the action of immune based adaptive controller for the DSTATCOM. In order to get desired performance from the AIS based adaptive controller, the 'm' constants shown in Fig. 4 (m_1 to m_8) are to be tuned first. This tuning is again carried out by PSO and the tuned constants are:
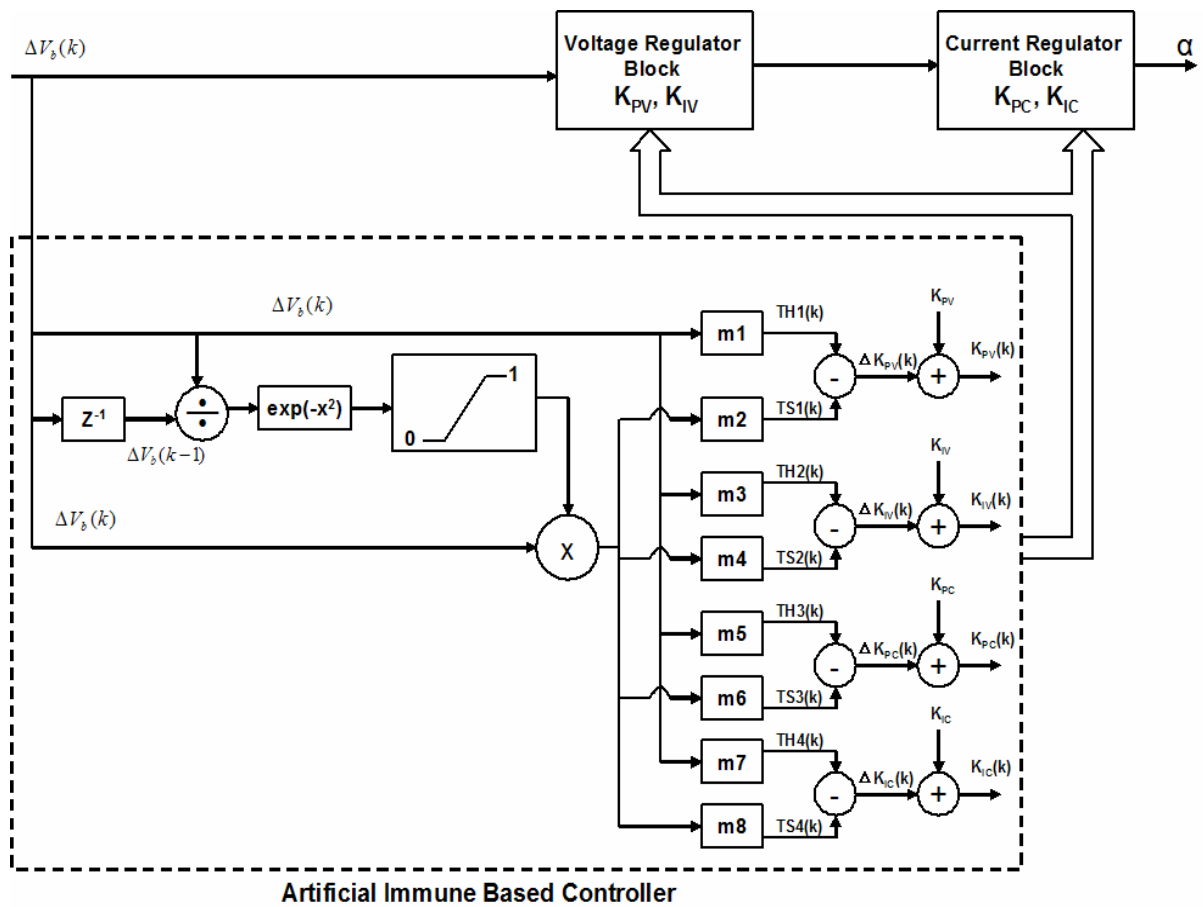
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Figure 4. Adaptive Controller for the DSTATCOM

$m_1 = 189.06$, $m_2 = 118.21$, $m_3 = 122.61$, $m_4 = 416.7$
$m_5 = 5.01$, $m_6 = 1.33$, $m_7 = 450.37$, $m_8 = 220.11$.

V. TEST SYSTEM

The ship power system actually consists of four generators and two propulsion motors. But, to study the effect of DSTATCOM, a simplified model consisting of one generator of 36 MW/45 MVA and a propulsion motor of 20 MW is considered in this paper. The single line diagram of the test system is shown in Fig. 5. The model of the test system is built in MATLAB/SIMULINK environment.
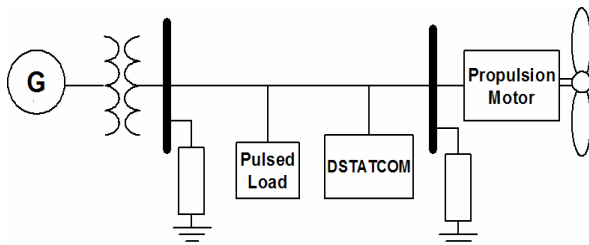

Figure 5. Test Ship Power System

The pulsed load of 10 MW/10 MVAR, 15 MW/15 MVAR and 20 MW/20 MVAR having 200 milliseconds duration are used for tuning the controller parameters using PSO. Whereas the performance of the immune based adaptive controller is observed for pulsed loads of 20 MW/40 MVAR having duration of 100 and 200 milliseconds and 20 MW/50 MVAR for 200 milliseconds.

VI. RESULTS

As the DSTATCOM controller is tuned by PSO for a specific operating range, it achieves an innate immunity towards the pulsed load disturbances close to this range. So, AIS based adaptive controller action cannot be distinguished for a pulsed load of the same range. To observe the effect of AIS control strategy three unusual disturbances are simulated. The first one is a pulsed load of 20 MW/40 MVAR with duration of 100 milliseconds. The second one is of same magnitude but having duration 200 milliseconds and the third one is the worst operating condition with a pulsed load of 20 MW/50 MVAR and duration 200 milliseconds.

The performance of the PSO tuned DSTATCOM controller and the AIS based adaptive controller are compared with each other as well as with a system having no DSTATCOM connected to it. Figs. 6, 7 and 8 represent the situations where all the three performances are compared for three unexpected operating conditions mentioned above.
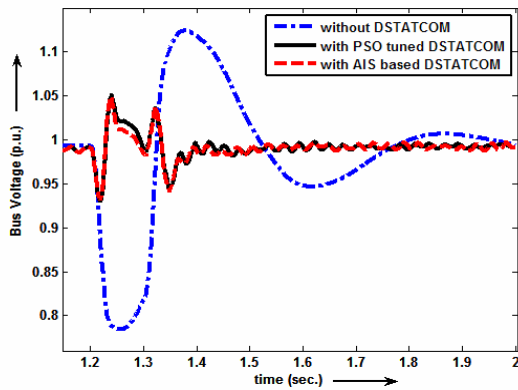
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Figure 6. Performance Comparison for Pulsed Load of 20 MW/40 MVAR for 100 milliseconds
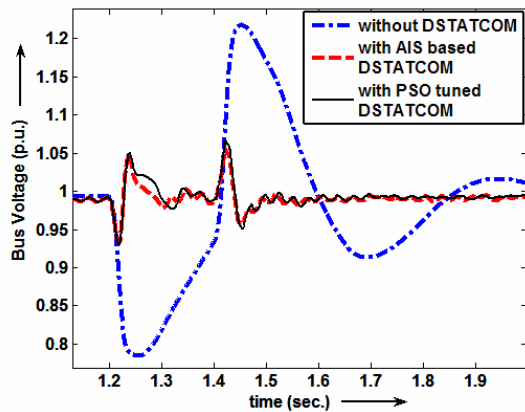

Figure 7. Performance Comparison for Pulsed Load of 20 MW/40 MVAR for 200 milliseconds
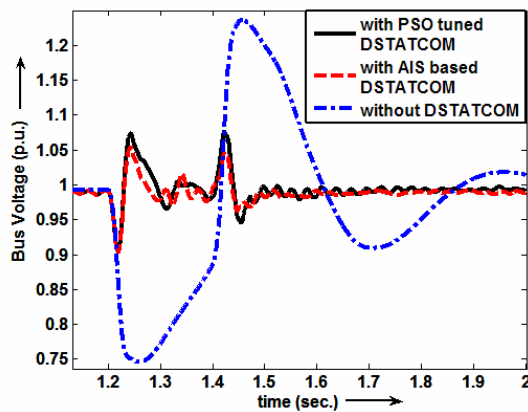

Figure 8. Performance Comparison for Pulsed Load of 20 MW/50 MVAR for 200 milliseconds

It is found that both PSO tuned controller and the AIS based adaptive controller are performing far better than the system without a DSTATCOM. But very insignificant improvement is observed with the AIS based adaptive controller with respect to the PSO tuned controller for the first operating condition, i.e. with a pulsed load of 20 MW/40 MVAR and duration 100 millisecond. But, as the duration of the pulsed load is increased to 200

milliseconds keeping the magnitude constant, the severity of the pulsed load is increased and the AIS based adaptive control comes into play. Fig. 9, which is basically the zoomed version of Fig. 7, shows the improvement due to the AIS based control with respect to the PSO tuned controller. It is found that the peak value of the bus voltage is reduced by a small amount and the post disturbance voltage ripples damp out earlier.

If the operating condition is changed farther to increase the magnitude of the pulsed load to 20 MW/50 MVAR, the performance of the AIS based control is much better than the PSO tuned controller. This is shown by Fig. 10, which is again a zoomed version of Fig. 8. Here, both the peak overshoot and the settling time are reduced by a noticeable amount. So, it is evident from the figures that the performance of the AIS based adaptive control strategy gradually becomes significant with the increased severity of the system disturbance. There lies the effectiveness of this control strategy.

Finally, Figs. 11 and 12 show the variation of the control parameters in dynamic condition for the third operating point. This variation indicates how the AIS based adaptive control action is taken and how the parameters adjust themselves with the continuously changing environment.
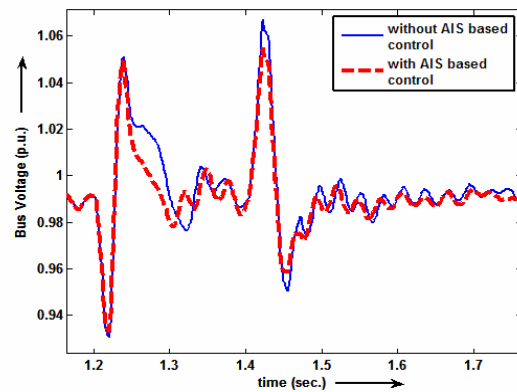

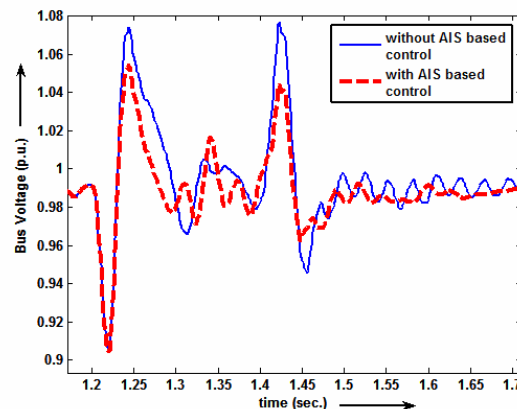Figure 9. Performance Comparison between PSO and AIS Based Controller for 20 MW/40 MVAR Pulsed Load

Figure 10. Performance Comparison between PSO and AIS Based Controller for 20 MW/50 MVAR Pulsed Load
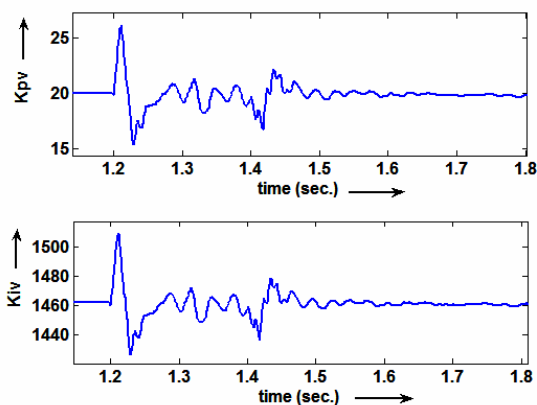
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Figure 11. Variation of Controller Parameters *Kpv* and *Kiv* in Dynamic Condition
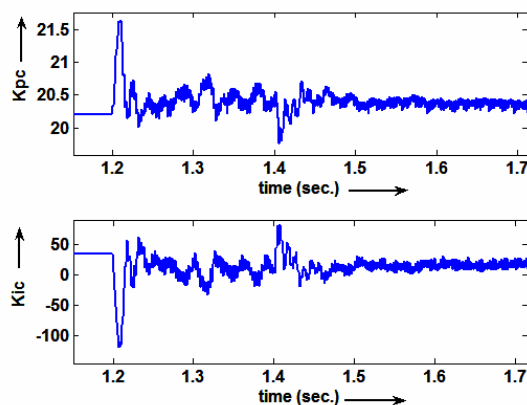

Figure 12. Variation of Controller Parameters *Kpc* and *Kic* in Dynamic Condition

VII. CONCLUSIONS

This paper has presented the application of DSTATCOM to improve the power quality in a ship power system during and after pulsed loads. In addition, an adaptive control strategy of DSTATCOM based on artificial immune system has been developed. The innate immunity to common disturbances is achieved using a controller whose optimal parameters are determined by particle swarm optimization algorithm. For unknown disturbances, adaptive immunity is developed based on immune feedback principles. The simulation results show that the voltage regulation at the point of common coupling is much better with a DSTATCOM. Also, it is evident from the results, that as the system faces severe and unexpected disturbances, the role of AIS based adaptive controller becomes more prominent. This ensures

a better survivability of an electric ship against unusual system disturbances created by pulsed loads.

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