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Real Time Implementation of an Artificial Immune System Based Controller for a DSTATCOM in an Electric Ship Power System

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***Abstract*— A new adaptive control strategy based on Artificial Immune System (AIS) for a DSTATCOM in an electric ship power system is presented in this paper. DSTATCOM is a shunt compensation device, which can be used to improve the power quality during the pulse power requirements in a naval shipboard system. The role of DSTATCOM controller is very important to meet this objective. In this paper, the DSTATCOM controller parameters are first tuned by Particle Swarm Optimization (PSO) technique, so that it can provide innate immunity to common system disturbances. Then, these optimum parameters are modified online by an artificial immune system (AIS), which provides adaptive immunity to unusual system disturbances. To evaluate the performance of the proposed control strategy, a simplified model of the ship system consisting of a 45 MVA main generator, a 5 MVA auxiliary generator and a 36 MW propulsion motor is simulated in a real-time environment. The effectiveness of the PSO and AIS based adaptive controller is demonstrated on a Real Time Digital Simulator based test system for pulsed loads of different magnitudes and durations.**

Keywords- artificial immune system; DSTATCOM; electric ship power system; intelligent control; particle swarm optimization; power quality

I. INTRODUCTION

In an all-electric ship power system, the loads like rail guns, aircraft launchers, etc. are referred as pulsed loads [1]. These pulsed loads are generally associated with severe voltage dips due to its high power requirement for a very short period of time. Therefore, in order to increase the survivability of the all-electric navy ships in battle condition, the negative effects of pulsed loads are to be minimized. DSTATCOM or distribution static compensator can be a probable solution to this problem. DSTATCOM is a Voltage Source Inverter (VSI) based shunt compensation device, which can inject power to the bus as per requirement [2]. The sophisticated power electronics based control of DSTATCOM helps it to regulate the bus voltage by controlling the injected power efficiently. The typical structure of a DSTATCOM is shown in Fig. 1.

The performance of the DSTATCOM is very much dependent on the DSTATCOM controller. The investigations on the control strategies of DSTATCOM primarily focus on its topology and the type of application. For example, papers [2]-[5] present different control strategies based on the multi-level inverter topologies of shunt compensators. Attempts have been made to make the controller robust by applying sliding mode control strategy as in [6] and [7]. But, these control strategies are not adaptive to the system dynamics. Also, most of the conventional control schemes of DSTATCOM have several PI controllers. The tuning of PI controllers is a complex task for the systems having power electronics equipments. 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 [8] and [9] are based on Artificial Neural Networks (ANNs). In [8], 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 [9], 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.

In this paper an adaptive control strategy for a DSTATCOM based on Artificial Immune System (AIS) is presented. 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 [10]. Abnormal changes in the system response are identified and acted upon without having any prior knowledge [11]. AIS controller parameters are first tuned by particle swarm optimization (PSO), so that it can provide innate immunity to common system disturbances. As a result, the AIS based DSTATCOM controller exhibits both innate and adaptive immune system behaviors.

The proposed control strategy of DSTATCOM in ship power system is validated on a Real-Time Digital Simulator (RTDS) platform. The advantage of RTDS is that, it can represent the dynamics of a system almost as close as the real system. The fast acting power electronic switching devices are also simulated in such a way that it can be interfaced with a practical hardware system any time. The tuning of the controller parameters using PSO is carried out on a digital signal processor (DSP) interfaced to the RTDS. The AIS based control strategy is also implemented on a DSP.

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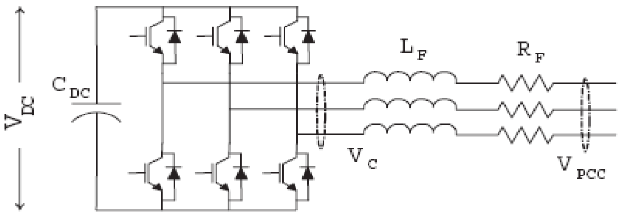

Figure 1. Schematic diagram of DSTATCOM.

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:

$$P = \frac{V_{PCC} V_C \sin\alpha}{X} \tag{1}$$

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

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.

The control strategy for the DSTATCOM adopted in this paper is represented by Fig. 2. Here, the PLL generates a reference angle. This reference angle is used to calculate d-q component of the DSTATCOM current using a-b-c to d-q-0 transformation. Also this angle is used to calculate the a-b-c voltage from its d and q components and to generate a triangular wave for the sine-triangle modulator to produce required firing pulses. The controller uses a two layer decoupled control scheme to keep the bus voltage and the DC capacitor voltage at constant level [12]. The PI controllers of the outer layer (PI(1) and PI(2)) generate the reference currents I_{d_ref} and I_{q_ref} for the inner loop. The other two PI controllers (PI(3) and PI(4)) just keeps track of the reference.

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 [13], [14]. 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 [15].

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

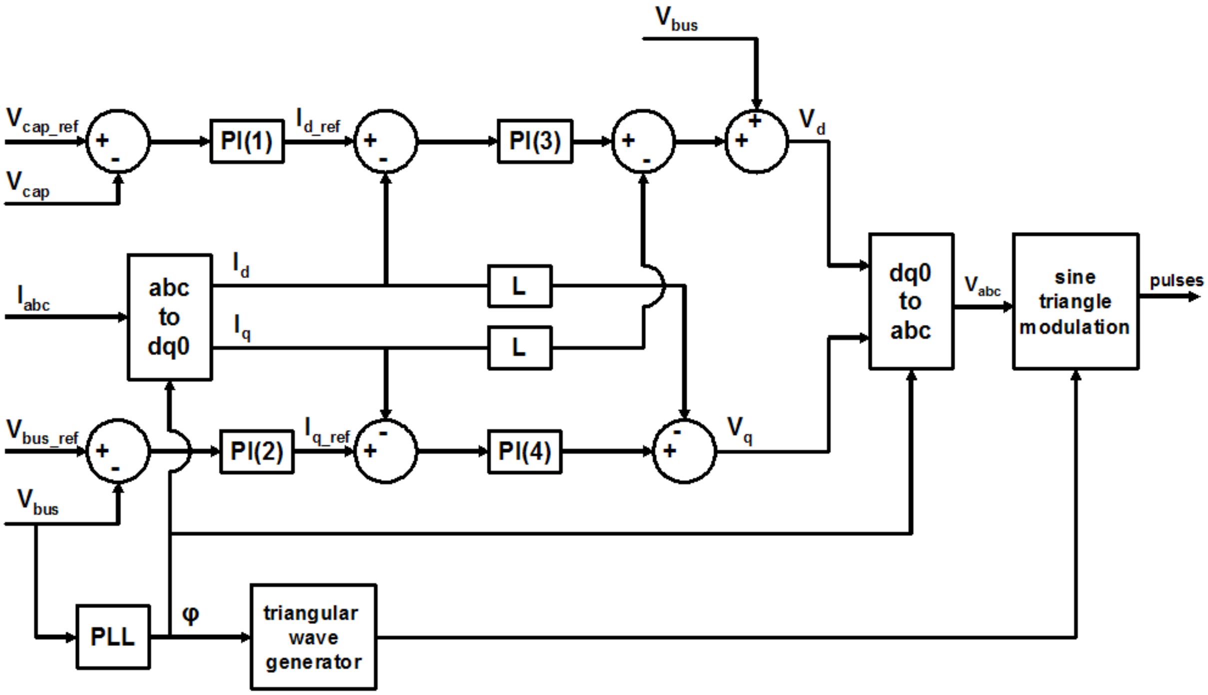

Figure 2. Control Structure for the DSTATCOM.

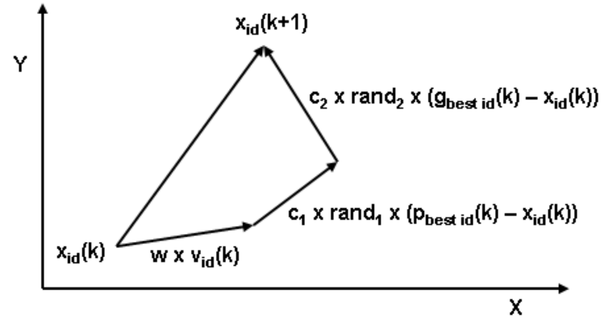

Figure 3. Concept of changing a particle's position in two dimensions.

a) $x_{id}(k)$ is the current position of i^{th} particle with *d* dimensions at instant *k*.
b) $x_{id}(k+1)$ is the position of i^{th} particle with d dimensions at instant *(k+1)*.
c) $v_{id}(k)$ is the initial velocity of the i^{th} particle with *d* dimensions at instant k.
d) $v_{id}(k+1)$ is the initial velocity of the i^{th} 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.
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 i^{th} particle of *d* dimension is given by:

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

The position vector of the i^{th} particle of *d* dimension is updated as follows:

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

In this paper, the first two PI controllers PI(1) and PI(2) of Fig. 2 are tuned by PSO. In order to find out the optimum controller parameters, the PSO algorithm is implemented on an Innovative Integration M67 which is based on the Texas Instruments TMS3206701 DSP. The M67 operates at 160 MHz and is equipped with two A/D conversion and D/A conversion modules. The rest of the system is built in RSCAD software, which is the RTDS software. The analog signal provided to the M67 is the AC bus voltage deviation, which comes from the RTDS. This is converted to digital signal through the A/D block of the DSP and is used to calculate the fitness value of the controller parameters. The four parameters (K_{p1} = proportional gain of PI(1), K_{i1} = integral gain of PI(1), K_{p2} = proportional gain of PI(2), K_{i2} = integral gain of PI(2)) are the dimensions of each particle of the swarm. The particle positions are initiated randomly inside the DSP and are sent to the RTDS as analog voltage signals within the range of -10 to +10 Volts. These voltages are scaled proportionately inside the RTDS and used as the PI controller parameters for each iteration. The calculation of *pbest* and *gbest*, the update of position and velocity, all are performed inside the DSP. The hardware set up of the experiment carried out including the RTDS and DSP is shown in Fig. 4.

Here, bus voltage regulation is one of the main objectives of the DSTATCOM. Hence the cost function is considered in such a way that the minimization of the cost function gives better regulation. The mathematical expression for the cost function is as follows:

$$J = \sum_{k=1}^{T/\Delta t} (\Delta v(k))^2 \cdot \Delta t \tag{5}$$

Where
T = Total time of simulation after the application of pulsed load
Δt = Sampling interval
k = Sampling instant
$\Delta v(k)$ = Bus voltage deviation at k^{th} sampling instant.

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 is taken to be 20. The optimum PI controller parameters found by PSO are:

K_{p1} = 30.0,
K_{i1} = 50.02,
K_{p2} = 124.7,
K_{i2} = 2.08.

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 [10].

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 $\Delta V_b(k)$ and also the deviation of the capacitor voltage $\Delta V_{CAP}(k)$. The first PI controller (PI(1)) works with an objective of keeping the capacitor voltage constant, i.e. it will try to keep

$\Delta V_{CAP}(k)$ equal to zero. Similarly, other PI controllers (PI(2)) tries to keep $\Delta V_b(k)$ equal to zero. In terms of Artificial Immune System the aforesaid functions of the PI controllers can be made adaptive considering the helping and suppressing actions of the helper and suppressor *T* cells. The mathematical representation shown here is only for the antigen $\Delta V_b(k)$. The same analysis will also hold for the antigen $\Delta V_{CAP}(k)$.

The output from the helper *T* cells stimulated by the antigen $\Delta V_b(k)$ is given by

$$TH(k) = m\Delta V_b(k) \tag{6}$$

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

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

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

$$f(x) = \exp(-x^2) \tag{8}$$

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

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

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. 5 illustrates this action of immune based adaptive controller for the disturbance $\Delta V_b(k)$, where the parameters for the PI controller 2 are modified online following AIS. A similar figure can be drawn for the disturbance $\Delta V_{CAP}(k)$, which dynamically modifies the parameters associated with PI controllers 1.

In this paper, the AIS based control strategy is implemented inside the DSP. Each AIS based PI controller is associated with four 'm' constants as shown in Fig. 5. So there are as a whole eight *'m'* constants (m_1 to m_8) for two PI controllers which are to be tuned using PSO. These eight *'m'* constants are the dimensions of each particle of the swarm and are initiated randomly inside the DSP. Here the signals $\Delta V_b(k)$ and $\Delta V_{CAP}(k)$ are sent to the DSP from RTDS in order to take the helping and suppressing actions. Also, $\Delta V_b(k)$ is used for the calculation of cost function as before. The control signal $B(k)$, which is basically the adaptive deviation in the values of proportional and integral gains of the PI controllers, are generated by the AIS based controller inside the DSP. These signals are scaled and brought within the range -10 to +10 Volts and sent back to RTDS. Inside the RTDS, those signals are again restored to their original values and added to the optimal values of the PI controller parameters to make them adaptive.

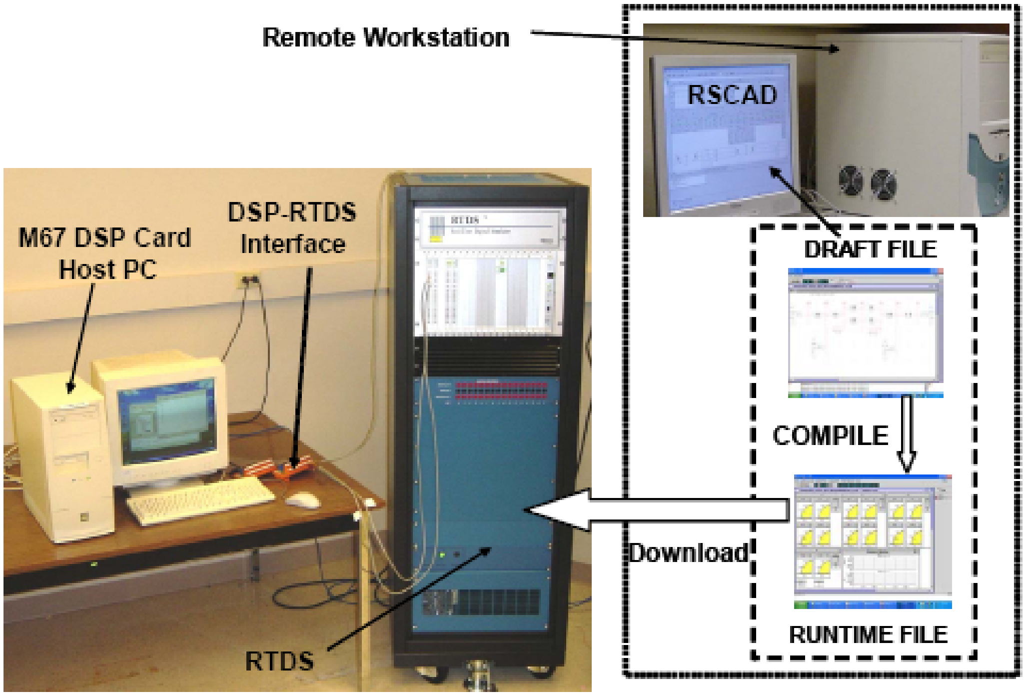

Figure 4. Laboratory hardware set-up including RTDS and DSP.

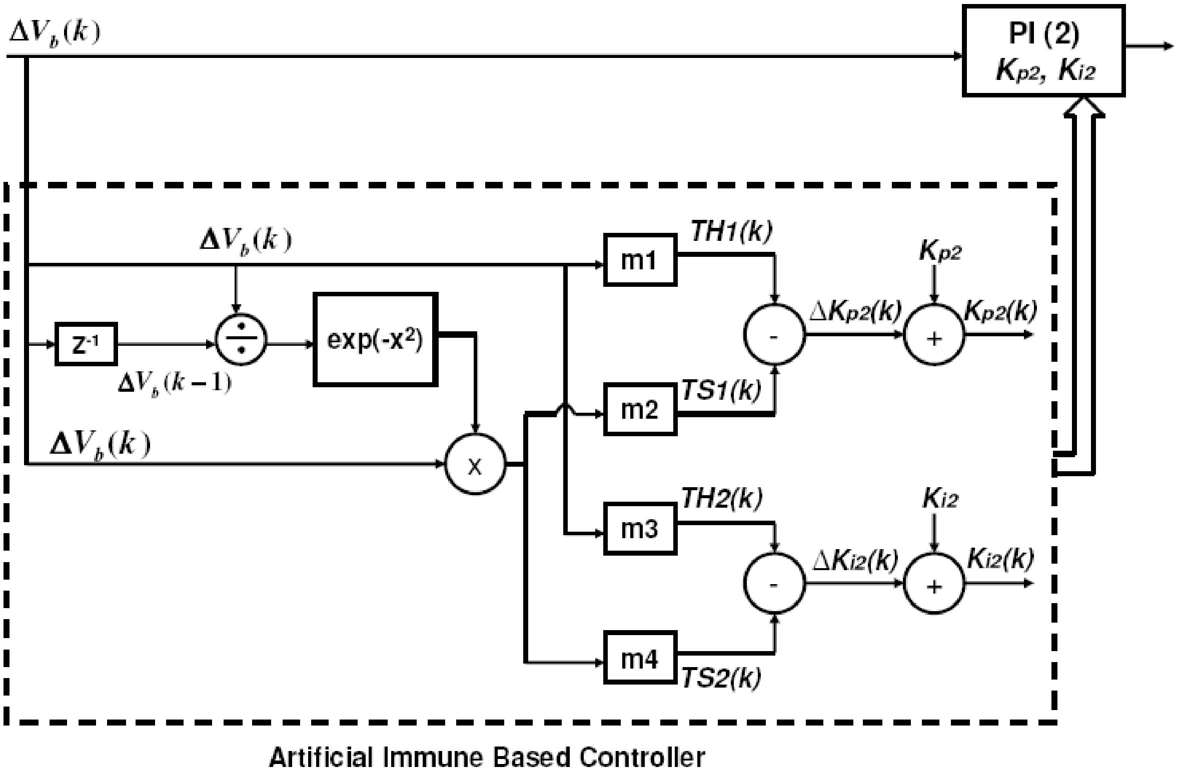

Figure 5. Adaptive PSO-AIS based controller for a DSTATCOM.

V. TEST SYSTEM

To validate the performance of the proposed AIS based controller of DSTATCOM in ship power system, a model of an electric ship is built in a real-time environment. The advantage of the RTDS is that, it can represent the dynamics of a system almost as close as the real system. Since the ship power system has a symmetrical network; the impact of the pulsed loads and the effects of DSTATCOM can easily be demonstrated by considering two generators and one propulsion motor. The test system in this paper consists of one main generator of 45 MVA, one auxiliary generator of 5 MVA and one propulsion motor of 36 MW with voltage source converter drives. Fig. 6 shows the schematic diagram of the test system and Fig. 7 shows the RSCAD model used in this paper. Small time-step model (1μs) of the propulsion motor and the Voltage Source Converter (VSC) are built up and interfaced with the remaining large time-step portion of the model through two interfacing transformers (Fig. 8).

VI. RESULTS

The optimal PI controller parameters and the *'m'* constants in Fig. 5 are found using PSO for a pulsed load of 20 MW and 50 MVAR with a duration of 40 cycles. The performance of the AIS based controller is compared with a system having no DSTATCOM connected to it. Fig. 9 shows the characteristics of bus voltage deviation with the disturbance for which the controller parameters are tuned. It is clearly observed that the AIS based DSTATCOM reduces the voltage dip as well as the peak overshoot by a substantial amount. To check the robustness of this controller, pulsed loads of different magnitude and duration are now applied. To represent a less severe pulsed load, the duration is made 30 cycles and the reactive power is changed to 40 MVAR keeping the active power constant. Then both the magnitude and duration of the pulsed loads are increased in steps. Two more cases of severe pulsed loads (40 cycles and 60 MVAR and 50 cycles and 60 MVAR) are simulated. Figs. 10, 11 and 12 represent the bus voltage characteristics for the above mentioned cases. Again, it is found that in all the cases, the AIS based control strategy is performing well which establishes the effectiveness of this control strategy for a ship power system. Finally, the dynamic variations of the two PI controller parameters are shown for a pulsed load of 40 cycles and 20MW/60 MVAR. The adaptive modification of the parameters in running condition due to the AIS control strategy is clearly observed from Fig. 13.

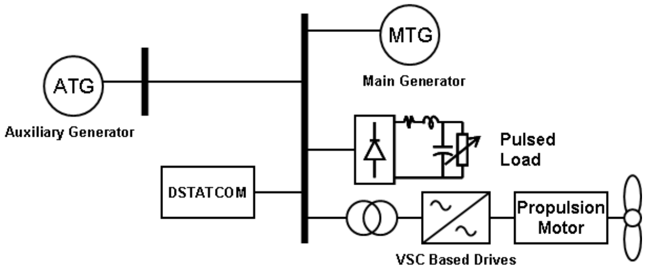

Figure 6. Schematic diagram of the test system

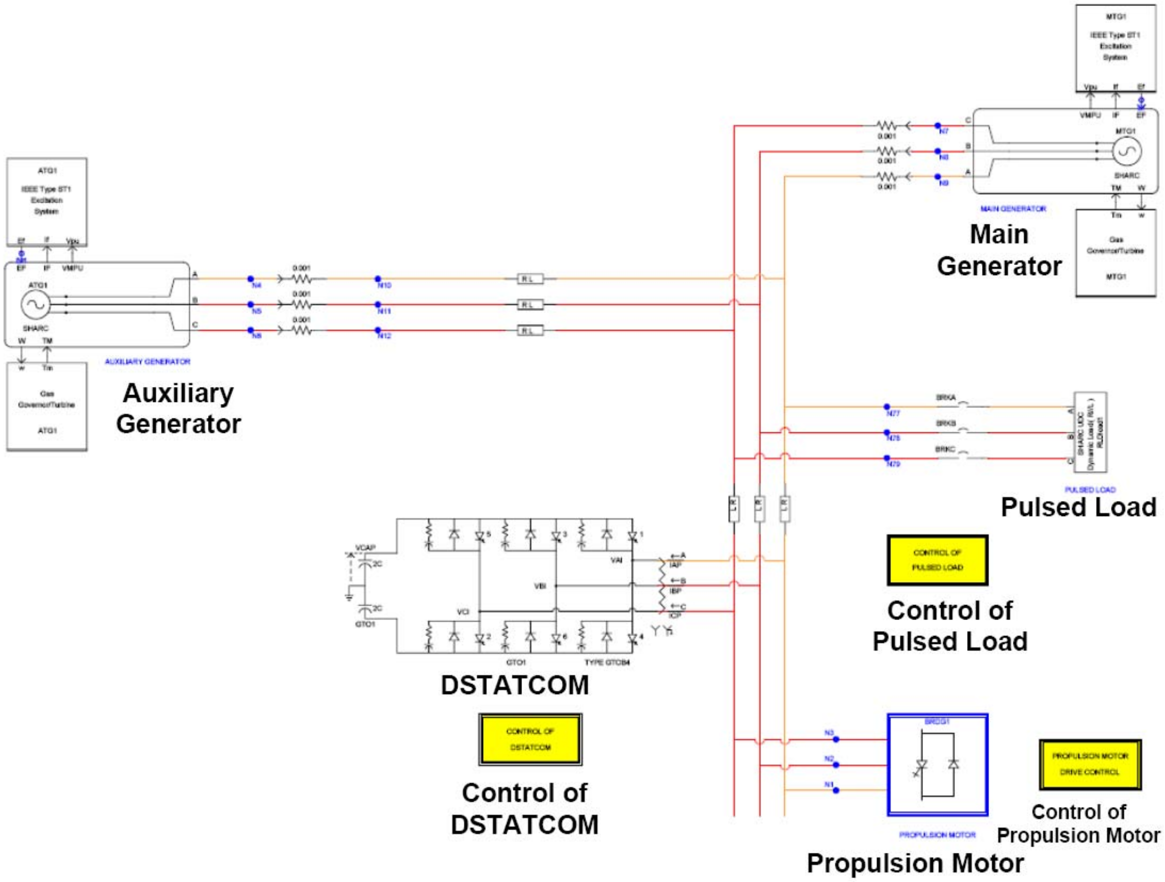

Figure 7. RTDS model of the test system depicting the different modules.

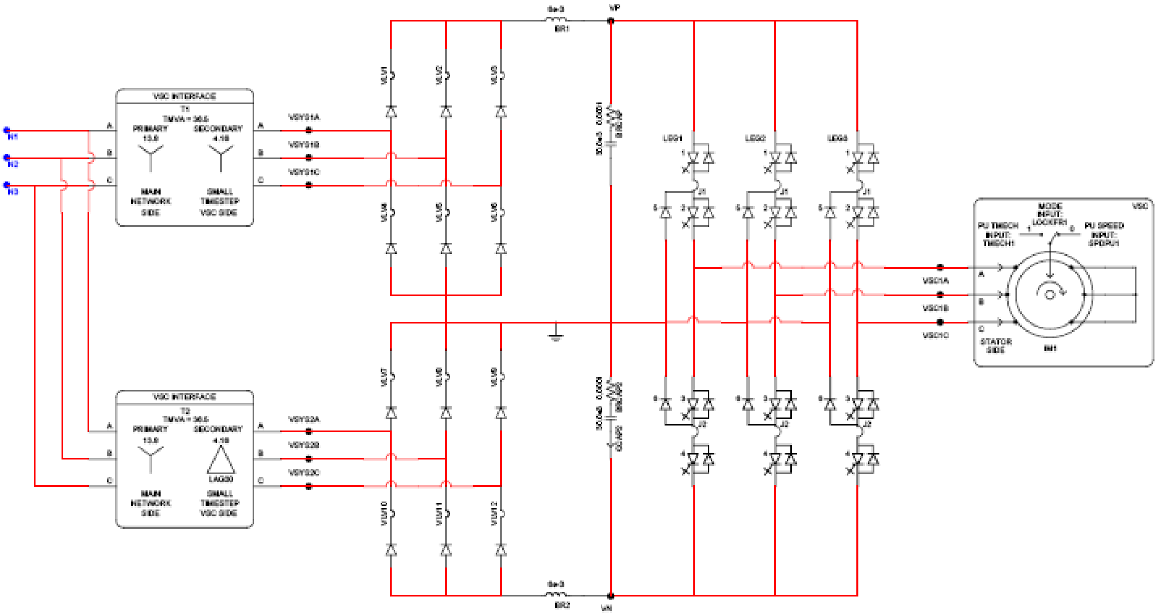

Figure 8. Small time-step model of the propulsion motor with VSC.

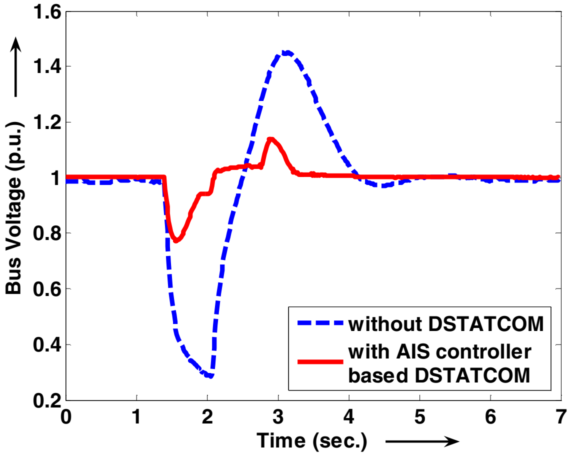

Figure 9. Performance comparison for pulsed load of 20 MW/50 MVAR for 40 cycles.

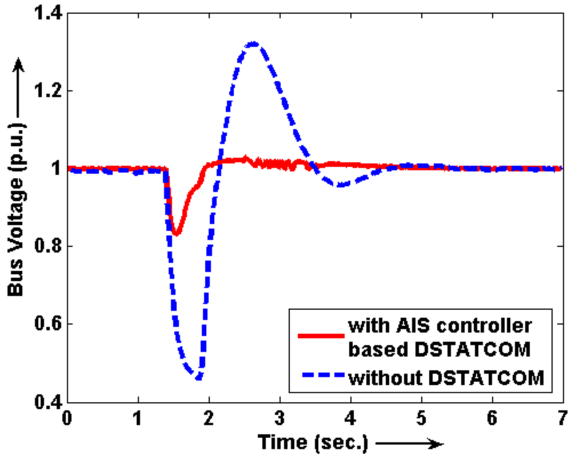

Figure 10. Performance comparison for pulsed load of 20 MW/40 MVAR for 30 cycles.

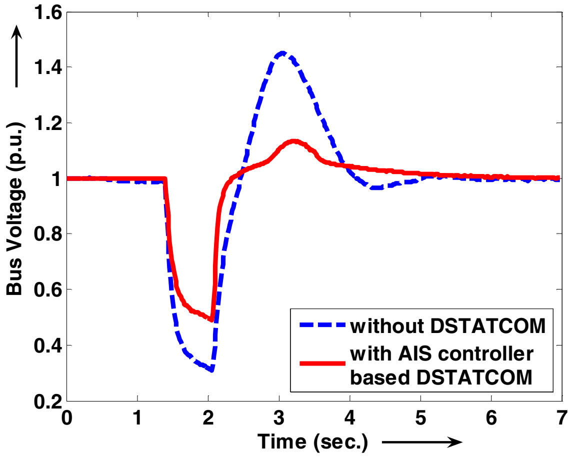

Figure 11. Performance Comparison for Pulsed Load of 20 MW/60 MVAR for 40 cycles.

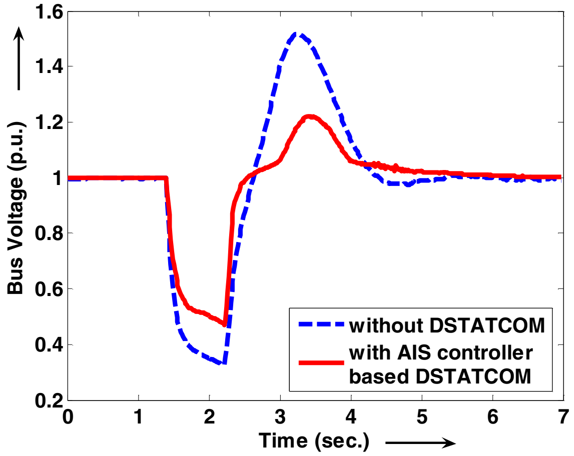

Figure 12. Performance comparison for pulsed load of 20 MW/60 MVAR for 50 cycles.

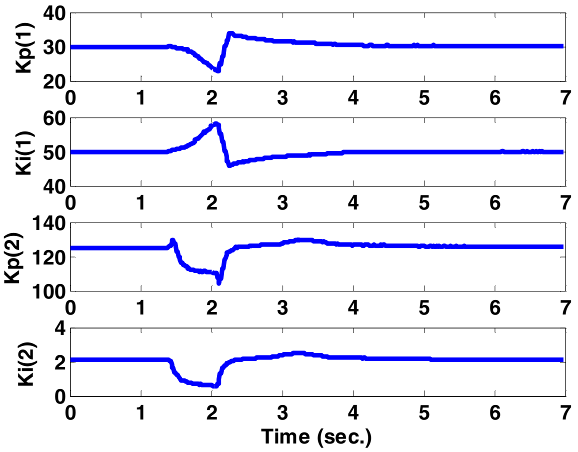

Figure 13. Dynamic variation of the PI controller parameters.

VII. CONCLUSION

The real-time implementation of an artificial immune system based control strategy for an electric ship power system has been presented in this paper. The ship power system is simulated on a Real Time Digital Simulator and the AIS control strategy is implemented on the DSP including the PSO implementation for tuning the AIS parameters.

The optimal parameters of the PI controller are first tuned by PSO to provide the innate immunity to the system. The adaptive immunity is developed based on immune feedback principle. The experimental results show that the AIS controller based DSTATCOM is successfully in reducing the bus voltage deviations under a broad range of pulsed power disturbances which conforms its effectiveness in a ship power system. Future work involves the coordination of DSTATOM control with the excitation controls of the generators and other controllable energy storage devices.

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