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A DSTATCOM Controller Tuned by Particle Swarm Optimization for an Electric Ship Power System

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***Abstract*-- In an all-electric ship power system, the power quality problems mainly arise due to the pulsed loads, which cause the degradation of the overall system performance. The paper proposes the application of DSTATCOM to improve these power quality problems of an electric ship. DSTATCOM is a shunt compensation device, which regulates the bus voltage by injecting reactive power during the pulsed load operations. The control strategy of DSTATCOM plays an important role to meet the objectives. The paper proposes a controller design strategy which is based on Particle Swarm Optimization (PSO). PSO, an algorithm that falls into swarm intelligence family, is very effective in solving non-linear optimization problems. Here, the optimal parameters of a controller are found using PSO. To evaluate the performance of the proposed controller, a simplified model of a ship power system is developed in MATLAB/SIMULINK environment, which comprises of a 36 MW generator, 10 MW propulsion motor and pulsed loads of different values of real and reactive power. The effectiveness of the DSTATCOM and the PSO based controller are examined on the test system for pulsed loads of 100, 200 and 500 millisecond durations and also for a pulse train of 100 millisecond interval.**

***Index Terms* - DSTATCOM, Electric Ship Power System, Intelligent Control, Particle Swarm Optimization, Power quality.**

I. INTRODUCTION

The all-electric ship power system 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 served by electrical energy as a part of the same network. Among the loads, the pulsed loads have the most detrimental effect on the power quality of a ship's power distribution system as it requires very high amount of power for a very short period of time. To increase the survivability of the navy ships under battle conditions, the negative effects of these pulse loads are to be minimized. There is ongoing work today to study the impact of pulsed loads and also to find out probable solutions to the problems created by them. Application of a series voltage injection type Flywheel Energy Storage System (FESS) is one of the approaches to mitigate voltage sag problems due to pulsed loads [1]-[2]. Some researchers used generator excitation control including nonlinear voltage control based on Lyapunov's direct method [3]. Another approach manipulates the power of propulsion motors to eliminate the destabilizing effect of pulsed loads [4]. This paper presents a completely new approach which suggests the use of DSTATCOM to improve the power quality of electric ship during pulsed load application. DSTATCOM is simply a Static Compensator of lower rating. 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 many more [5]. In this paper, the function of DSTATCOM in regulating the bus voltage is mainly investigated.

The performance of the DSTATCOM is very much dependent on the proper tuning of the DSTATCOM controller. But, to find the values of those control parameters mathematically, one has to deal with the detailed mathematical model of the system. With power electronics applications, the problem becomes more complex to handle. To overcome this problem, intelligent control techniques are used in this paper. Here, the optimal parameters of the two PI controllers in voltage regulator and current regulator blocks are found by Particle Swarm Optimization (PSO) technique.

The rest of the paper is organized as follows: Section II describes briefly the electric ship power system. Section III elaborates the operation of DSTATCOM and its control mechanism. Section IV deals with PSO technique and the method of designing the PSO based optimal controller. Section V presents the test system and the results which demonstrate the effectiveness of the DSTATCOM and the PSO tuned controller. Finally, the conclusions are given in Section VI.

II. ELECTRIC SHIP POWER SYSTEM

The integrated power system architecture of an electric

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ship conventionally constitutes of two main generators of 36 MW accompanied by two auxiliary generators of 4 MW. The main generators are interconnected among themselves by 4.16 kV AC buses through step-down transformers. Also, there are two propulsion motors connected to the AC buses. There are several rectifier units which convert the AC voltage to DC and feed the 1 kV DC buses. Most of the loads of ship power system are connected to DC buses. But pulsed loads are connected directly to one of the generator buses. The structure of a typical naval shipboard power system network is shown in Fig. 1 [6].

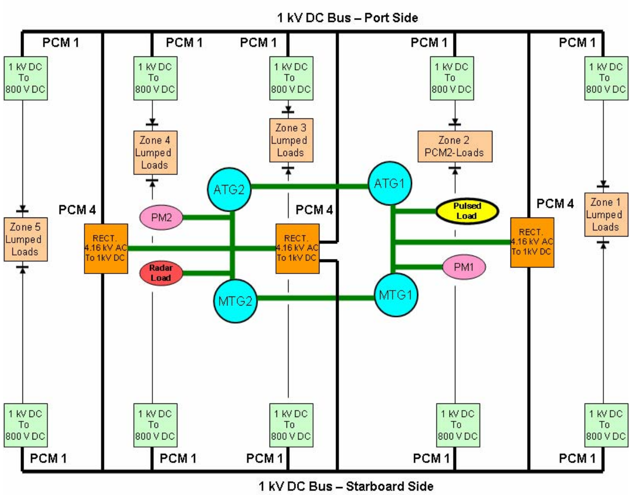

Fig. 1. Integrated All-Electric Ship Power System

Study of pulsed load is assuming increased importance nowadays. Pulsed loads have the inherent characteristics of destabilizing the power system, because it requires very high amount of energy for a short period of time. The power requirement for the pulsed loads can vary from hundreds of kilowatts to tens of gigawatts and the time duration can vary from several microseconds to few seconds with an interval of few seconds [6]. In this paper, the effects of pulsed loads ranging from 10 MW/10 MVAR to 20 MW/40 MVAR and of different durations are studied.

III. DSTATCOM

DSTATCOM or Distribution Static Compensator is a shunt device generally used in distribution system to improve power quality. The structure of a DSTATCOM is shown in Fig. 2.

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:

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

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

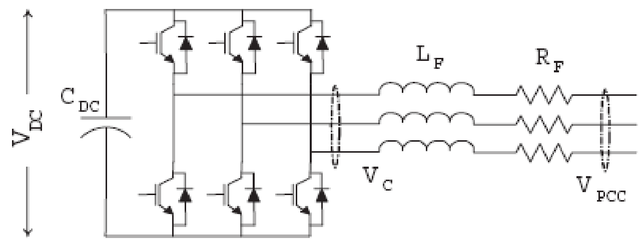

Fig. 2. Schematic diagram of DSTATCOM [7]

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 will flow 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. 3.

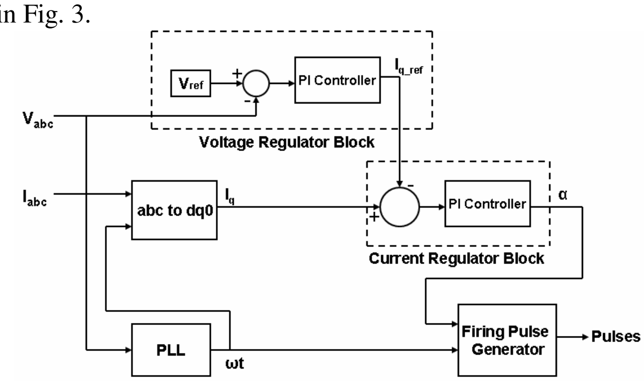

Fig. 3. Control Structure for the DSTATCOM

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 passes through a PI controller to generate 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. 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 pulsed load, 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 necessary reactive power flows from DSTATCOM to the bus.

IV. PSO Based Tuning of DSTATCOM Controller

Particle swarm optimization is a population based search algorithm simulated to replicate the motion of flock of birds and school of fishes [8], [9]. A swarm is considered to be a collection of particles, where each particle represents a potential solution to the 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 [9], [10].

Initially a population of random solutions is considered. A random velocity is also assigned to each individual particle with which they start flying within the search space. Also, each particle has a memory which keeps track of the previous best position of the particle and the corresponding fitness. This previous best value is called 'p_{best}'. There is another value called 'g_{best}', which is the best value of all the 'p_{best}' values of the particles in the swarm. The fundamental concept of PSO technique is that the particles always accelerate towards their 'p_{best}' and 'g_{best}' positions at each time step. Fig. 4 demonstrates the concept of PSO where,

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 the particle are updated according to the following equations. The velocity of the i^{th} particle of d dimension is given by:

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

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

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

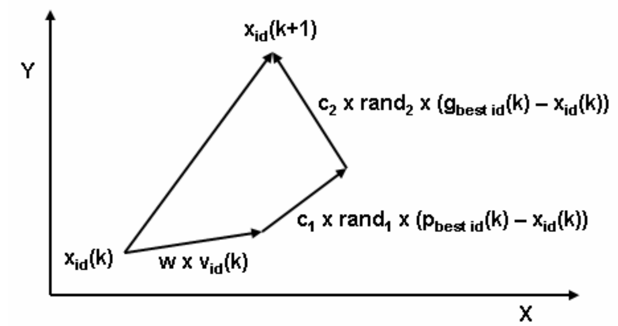

Fig. 4. Concept of changing a particle's position in two dimension [11]

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

This can be well-understood from the shaded region of the Fig. 5.

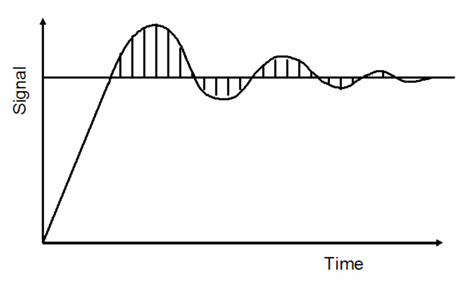

Fig. 5. The shaded area represents the cost function for PSO algorithm

This cost function is the fitness for each particle and is computed for every PSO iteration. The particle corresponding to the minimum value of fitness (i.e. minimum transient area) over entire search space is considered to be the global best solution of the problem. So, the positions of that g_{best} particle are taken as the final values of the two PI controller parameters.

Also, to find out a near optimal value of the controller parameters, the simulation is carried out for three different operating conditions. The pulse load magnitudes for those three conditions are 10 MW/10 MVAR, 15 MW/15 MVAR and 20 MW/20 MVAR respectively.

To get best search performance from the PSO algorithm, 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 25. Also the upper and lower limits of the velocity are set properly to 2.0 and -2.0 respectively to ensure quick convergence.

The flowchart for the tuning of DSTATCOM controller parameter using PSO is shown in Fig. 6.

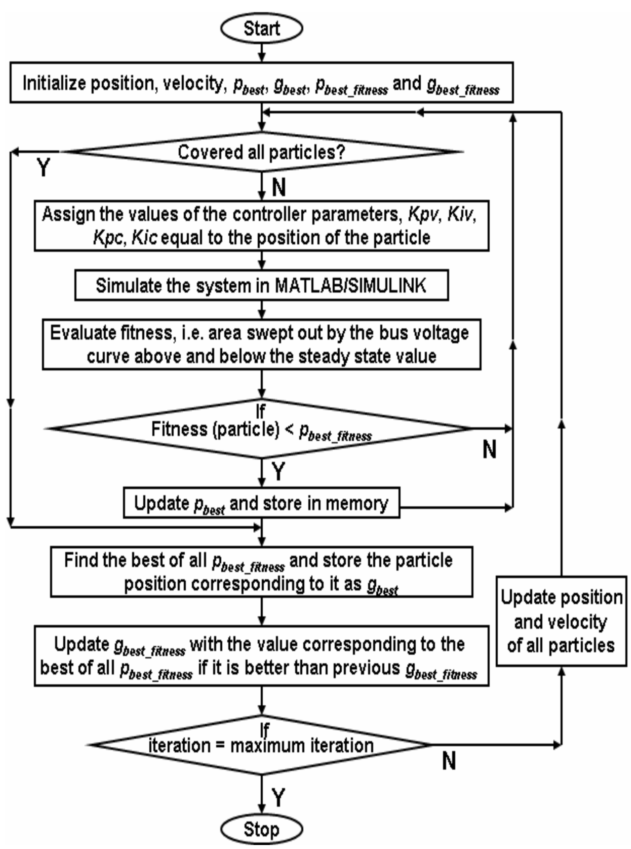

Fig. 6. Flowchart for tuning of controller parameters of DSTATCOM

V. Test System and Results

Since the ship power system has a symmetrical network; the impact of the pulsed loads can easily be demonstrated by considering only one generator and one propulsion motor. The single-line diagram of the test system is shown in Fig. 7.

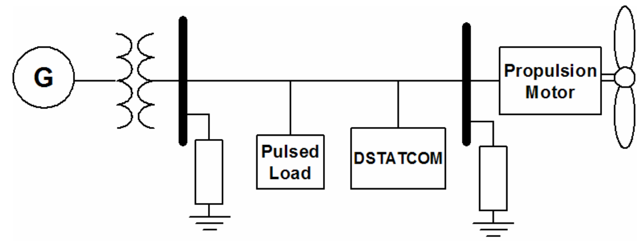

Fig. 7. Test System

The test system model consists of one generator of 36 MW/ 45 MVA and a propulsion motor of 10 MW. The model is built in MATLAB / SIMULINK environment.

The results can be divided into two categories: A) Results obtained during the tuning process. B) Results obtained during testing.

A. *Results obtained during the tuning process*

First, the optimum parameters are found applying PSO algorithm. The parameters are:

Kpv = 19.0,
Kiv = 1370.7,
Kpc = 25.9,
Kic = 34.5.

The fitness vs. iteration curve (Fig. 8) shows that the optimal solution is reached within 15 iterations only.

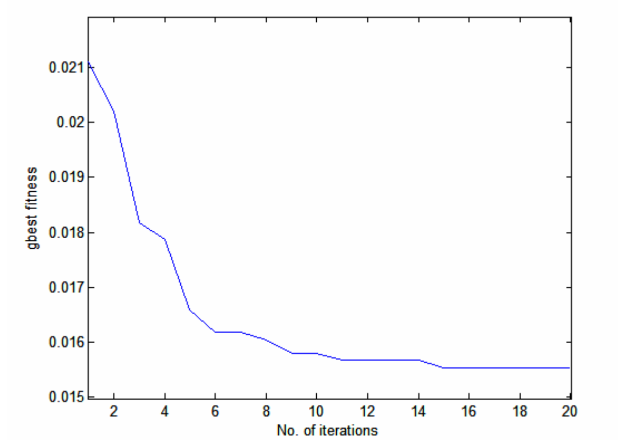

Fig. 8. Fitness vs. iteration curve

Fig. 9 shows the bus voltage characteristics with the PSO tuned DSTATCOM controller during the tuning process and is compared with a system having no DSTATCOM connected to it.

B. *Results obtained during testing*

Now the performance of the PSO tuned optimal DSTATCOM controller is compared with a manually tuned DSTATCOM controller and also with a system without DSTATCOM. The system is simulated with a pulsed load of 20MW/20 MVAR for 200 milliseconds. The result clearly shows the superiority of the PSO tuned DSTATCOM control over the others (Fig. 10).

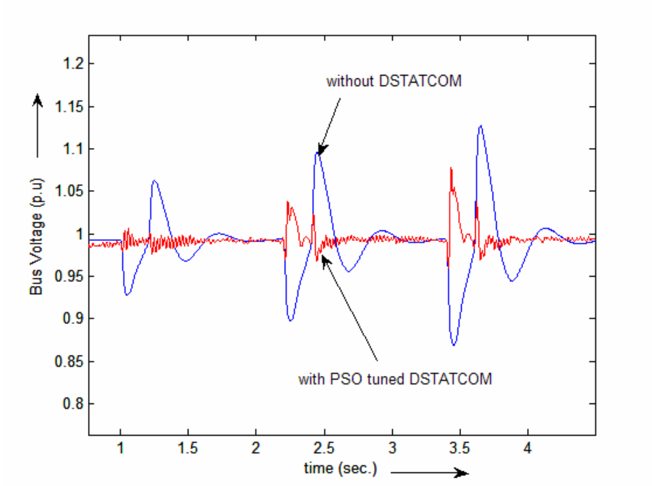

Fig. 9. Bus voltage characteristics with and without DSTATCOM as an outcome of the tuning process

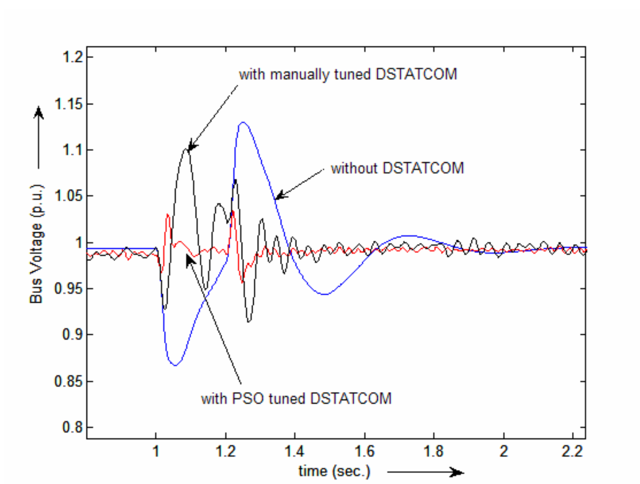

Fig. 10. Bus voltage characteristics of a PSO tuned DSTATCOM controller compared with manually tuned controller and system without DSTATCOM

Finally, in order to examine the robustness of the PSO tuned controller, three different tests are performed: one with a pulsed load of moderate magnitude and long duration (20 MW/20 MVAR, duration 500 milliseconds), the second one with a pulsed of high magnitude of reactive power (20 MW/40 MVAR) for 200 millisecond and the last one is a pulse train of three consecutive pulses of magnitude 20 MW/20 MVAR having a duration of 200 milliseconds each and with an interval of only 100 milliseconds between them. Fig. 11, Fig. 12 and Fig. 13 show the variation of bus voltages in the three cases respectively. It is clearly observed that the peak overshoot of the bus voltage oscillation and the settling time, both are reduced a lot with the PSO tuned controller. So, it is established from the results that the PSO tuned controller can successfully control the bus voltage during and after the application of the pulsed loads of wide range of magnitude and durations.

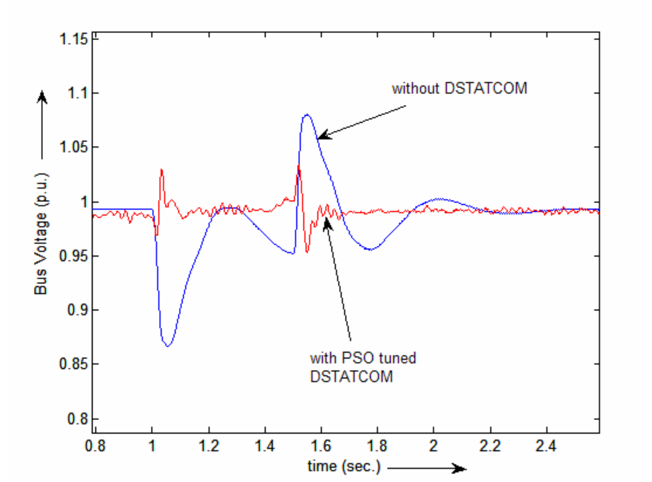

Fig. 11. Bus voltage characteristics with a pulsed load of 20 MW/20 MVAR, for 500 milliseconds with and without DSTATCOM

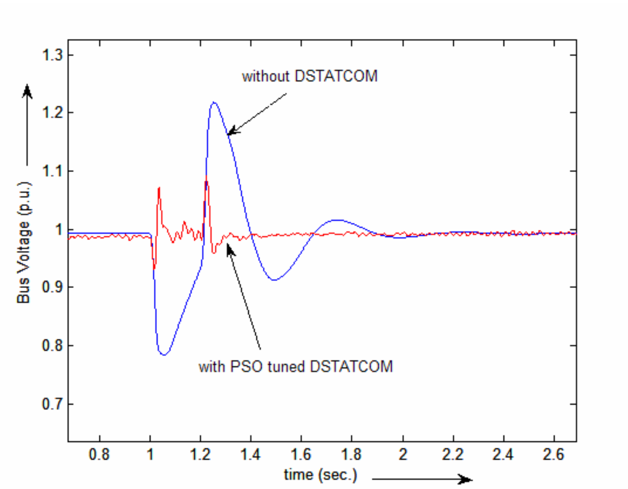

Fig. 12. Bus voltage characteristics with a pulsed load of 20 MW/40 MVAR, for 200 milliseconds with and without DSTATCOM

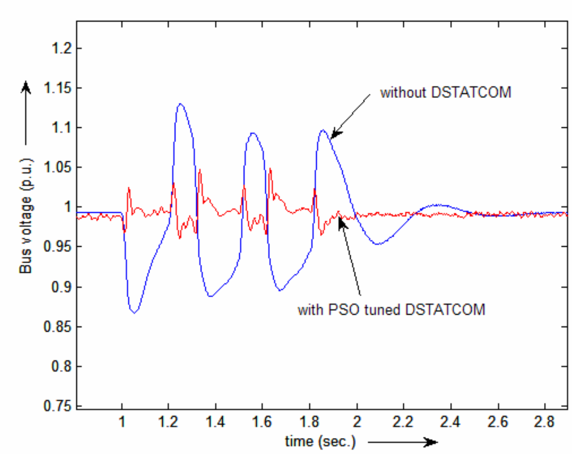

Fig. 13. Variation of bus voltage with a pulsed train of 3 pulses of 20 MW/20MVAR, each having a duration of 200 milliseconds and with an interval of 100 milliseconds

VI. Conclusion

This paper has presented a method to partly overcome the power quality problems in electric ship due to pulsed loads with the application of DSTATCOM. A typical control strategy of a DSTATCOM is considered in this paper and the optimal parameters of two PI controllers are found by using the particle swarm optimization technique. The robustness of the optimal controllers has been illustrated with pulsed loads of different magnitude and durations. It is found that the PSO tuned optimal controller based DSTATCOM is performing satisfactorily which establishes its effectiveness in ship power system.

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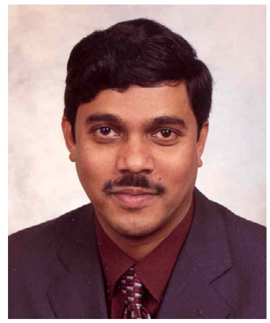
VIII. Biographies

Pinaki Mitra (Student Member'06) was born in 1974. He graduated in Electrical Engineering from Jadavpur University in 1997 and his Post Graduation was in Electrical Machines from the same University. At present he is a PhD student of the Real-Time Power and Intelligent Systems Laboratory, ECE Department, Missouri University of Science and Technology, Rolla, MO, USA.



Ganesh Kumar Venayagamoorthy (S'91, M'97, SM'02) received the B.Eng. degree (with first class honors) in electrical and electronics engineering from Abubakar Tafawa Balewa University, Bauchi, Nigeria, in 1994, and the MScEng and PhD degrees in electrical engineering from the University of Natal, Durban, South Africa, in 1999 and 2002, respectively. He was a Senior Lecturer with Durban Institute of Technology, South Africa, prior to joining the Missouri University of Science and Technology (Missouri S & T), in May 2002. He is currently an Associate Professor of Electrical and Computer Engineering and the Director of the Real-Time Power and Intelligent Systems Laboratory at UMR. He was a visiting researcher at the ABB, Corporate Research Center, Sweden during summer of 2007. Dr. Venayagamoorthy's research interests are in the development and applications of computational intelligence for real world applications including power systems stability and control, FACTS devices, power electronics, alternative sources of energy, sensor networks, collective robotic search, signal processing and evolvable hardware. He has published 2 edited books, 6 book chapters, 54 refereed journals papers and 200 refereed international conference proceeding papers. He has attracted close to US $ 4 million in research funding to date.

Dr. Venayagamoorthy was an Associate Editor of the IEEE TRANSACTIONS ON NEURAL NETWORKS from 2004 to 2007 and the IEEE TRANSACTIONS ON INSTRUMENTATION and MEASUREMENT in 2007. He is a Senior Member of the IEEE (USA) and the South African Institute of Electrical Engineers (SAIEE). He is also a member of the International Neural Network Society (INNS), The Institution of Engineering and Technology, U.K., and the American Society for Engineering Education. He is currently the IEEE St. Louis Computational Intelligence Society (CIS) and IAS Chapter Chairs, the Chair of the Working Group on Intelligent Control Systems, the Secretary of the Intelligent Systems subcommittee and the Vice-Chair of the Student Meeting Activities subcommittee of the IEEE Power Engineering Society, and the Chair of the IEEE CIS Task Force on Power System Applications. He has organized and chaired several panels, invited and regular sessions, and tutorials at international conferences and workshops.

Dr. Venayagamoorthy was a recipient of the 2007 ONR Young Investigator Program Award, the 2004 NSF CAREER Award, the 2006 IEEE Power Engineering Society Walter Fee Outstanding Young Engineer Award, the 2006 IEEE St. Louis Section Outstanding Section Member Award, the 2005 IEEE Industry Applications Society (IAS) Outstanding Young Member Award, the 2005 SAIEE Young Achievers Award, the 2004 IEEE St. Louis Section Outstanding Young Engineer Award, the 2003 INNS Young Investigator Award, the 2001 IEEE CIS Walter Karplus Summer Research Award, five prize papers from the IEEE IAS and IEEE CIS, a 2007 Missouri S & T Teaching Commendation Award. a 2006 Missouri S & T School of Engineering Teaching Excellence Award, and a 2007 and 2005 Missouri S & T Faculty Excellence Award. He is listed in the 2007, 2008 and 2009 editions of Who's Who in America, 2008 edition of Who's Who in the World and 2008 edition of Who's Who in Science and Engineering.