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Applications of Control Strategy for DSTATCOM in an Electric Ship Power System

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ABSTRACT: Distribution Static Compensator (DSTATCOM) is a shunt compensation device which used to solve power quality issue in distribution network. In an all-electric ship power system, power quality problem arise due to high energy consumption loads such as air craft launcher, missile launcher etc. In this paper we discussed the application of a DSTATCOM which improve the power quality in a ship power system during or after the pulse load applied. The control strategy of the DSTATCOM plays an very important role to maintain the voltage at the point of common coupling. A novel adaptive control strategy for the DSTATCOM based on Artificial Immune System (AIS) is presented in this paper. The optimal parameters of the controller are obtained first using the particle swarm optimization algorithm. This provides a sort of innate immunity (robustness) to common system disturbances. For unknown and random system disturbances, the controller parameters are modified online, thus providing adaptive immunity to the control system. The performance of the DSTATCOM and the AIS based adaptive control strategy is investigated first in MATLAB/SIMULINK based simulation platform. It is verified through a real-time ship power system implementation on a Real Time Digital Simulator (RTDS) and the control algorithm on a digital signal processor (DSP).

Keywords: Adaptive control, adaptive immunity, artificial immune system, DSP, DSTATCOM, electric ship power system, innate immunity, RTDS.

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 pulse loads are most detrimental for the power quality of ship power distribution system as they require a very high amount of energy for a very short period of time [1], [2]. In order to improve the survivability of a navy ship in battle conditions, a distribution static compensator (DSTATCOM) can be used to reduce the impact of pulse loads on the bus voltage and thus keep it at desired level. DSTATCOM is a voltage-source inverter (VSI) based shunt device [3] generally used in distribution system to improve power quality.

The main advantage of DSTATCOM is that, the current injection into the distribution bus can be regulated very efficiently by the sophisticated power electronics based control present in it. Another advantage is that, it has multifarious applications, e.g. it can be used for canceling the effect of poor load power factor, for suppressing the effect of harmonic content in load currents, for regulating the voltage of distribution bus against sag/swell etc. and also for compensating the reactive power requirement of the load and so on [4]. In this paper, the application of DSTATCOM to regulate voltage at the point of common coupling (PCC) is presented. But, these control strategies are not adaptive to changes in the system dynamics and hence the performance may not be satisfactory for unknown and random system disturbances. These types of disturbances are inevitable in naval shipboard systems, especially in battle conditions. Different ranges of rail guns and launchers may be used leading to a wide variation of pulse power disturbances. Adaptive control of a DSTATCOM becomes essential for survivability. Conventional controllers for DSTATCOMs are mainly based on PI controllers. The tuning of PI controllers is a complex task for a nonlinear system with lot of switching devices. In order to overcome these problems, Computational intelligence (CI) techniques can be used. Application of CI techniques in designing adaptive controller for DSTATCOM is not yet explored that much by the researchers. The PI controllers are replaced by a NN trained with the back propagation algorithm [10]. But, the training is carried out offline and hence the ANN based controller is not adaptive. In [11], a NN based reference current generator is used, which is a partially adaptive control strategy.

Here, though the reference generator adapts its NN weights online, but the DC voltage regulation is handled by conventional PI controllers. In this paper, a new 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 [12]. Abnormal changes in the system response are identified and acted upon without having any prior knowledge [13]. The AIS based DSTATCOM controller exhibits innate and adaptive immune system behaviors. Innate response is for common disturbances and requires controller parameters to be optimal. In this paper, the innate controller parameters are determined using the particle swarm optimization algorithm. The adaptive response is for new and unusual disturbances, and requires the controller parameters to be adaptive. The AIS strategy is applied in this paper for adaptation of these parameter.

The first type of control strategy is employed for the MATLAB based simulation. Here, 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 *VDC* 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.

The second type of control strategy consists of IGBT based inverter and is employed for the real-time implementation. It is represented by Fig. 3. 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 [15]. The PI controllers of the outer layer (PI(1) and PI(2)) generate the reference currents *Id_ref* and *Iq_ref* for the inner loop. The other two PI controllers (PI(3) and PI(4)) just keeps track of the reference.

II. TEST SYSTEM

As discussed earlier, the AIS based adaptive control strategy is evaluated with two test systems: A) MATLAB based test system; B) RTDS based test system.

A. MATLAB Based Test System

The ship power system actually consists of four generators and two propulsion motors. . But, due to its symmetry, the effect of DSTATCOM and the adaptive control action can be studied easily with a simplified system having only one generator and one propulsion motor. For this paper, a simulation model having a generator of 36 MW/45 MVA and a propulsion motor of 10 MW is built in Simulink using the Simpower system blocks. The single line diagram of this system is shown in Fig. 6. A pulse load of 20 MW/20 MVAR having 200 ms duration is used for tuning the controller parameters using PSO. Whereas the performance of the immune based adaptive controller is observed for pulse loads of 20 MW/40 MVAR having duration of 100 and 200 ms and 20 MW/50 MVAR for 200 ms.

B. RTDS Based Test System

A relatively detail model of a ship power system having one main generator of 45 MVA, one auxiliary generator of 5 MVA and one propulsion motor of 36 MW with voltage source converter drives is designed with the help of RSCAD software of RTDS. Fig. A-1 in the Appendix, shows the RSCAD model of the test system used in this paper. Small time-step model (1.5μs) of the propulsion motor and the VSC are built up and interfaced with the remaining large time-step portion of the model through two interfacing transformers (Fig. A-2). The optimal PI controller parameters and the *'m'* constants are determined using PSO for a pulse load of 20 MW/20 MVAR with a duration of 200 ms.

III. RESULTS

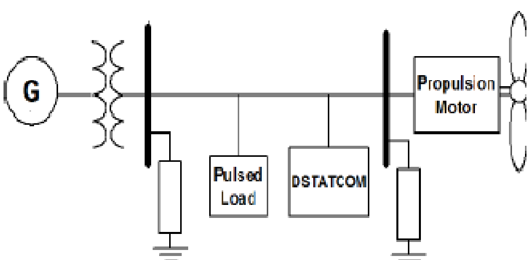
A. MATLAB Based Test System

As the DSTATCOM controller is tuned by PSO for a specific operating range, it achieves an innate immunity towards the pulse load disturbances close to this range. So, AIS based adaptive controller action cannot be distinguished for a pulse load of the same range. To observe the effect of AIS control strategy two unusual disturbances are simulated.

The first one is a pulse load of 20 MW/40 MVAR with duration of 200 ms and the second one is the worst operating condition with a pulse load of 20MW/50 MVAR and duration 200 ms.

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. 7 and 8 represent these cases.

It is found that both PSO tuned controller and the AIS based adaptive controller have a better performance than the system without a DSTATCOM. Also, 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 pulse 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. This is the benefit this adaptive control strategy. The variation in the controllers‘ parameters indicates how the AIS based adaptive control action is taken and how the parameters adjust themselves with the continuously changing environment. Once the system returns to normality, the innate controller parameters are restored. This is the beauty of such a controller strategy.

B. RTDS Based Test System

Based on the effective performance of the adaptive control strategy in the MATLAB environment, it is then implemented in a real-time environment. The real-time study has the following two sub-sections:

1. Realistic Pulse Load Representation: In a practical ship power system, pulse loads are measured in kilo Joules, Mega Joules or even in Giga Joules depending on the energy demand of the weapon systems. Due to the high energy demand of pulse loads, they are generally associated with an additional energy storage device like flywheel and a charging circuit [1]. The energy storage device is not the focus of this paper and hence is not considered here. But, a realistic representation of pulse load and its charging circuit is simulated in this paper. The charging circuit is represented by a variable resistance connected to the system via a diode rectifier and a charging capacitor (Fig. 13). Initially the resistance is kept very high so that it is almost open-circuited. Triggering of the pulse load means decreasing the value of the variable resistance suddenly, so that the capacitor discharges through it instantaneously and a charging current also flows from the system to the capacitor. Due to this sudden discharging and charging, a severe voltage dip and subsequent oscillation is noticed at the AC bus.

The performance of the AIS based control strategy is now studied with different values of realistic pulse load disturbances. When the values are smaller than 3 MJ, it is found that there is hardly any difference between the performance of the PSO tuned and AIS based controller. But, as the magnitude of the pulse load is increased, better performance is observed with the AIS based control. The performances of PSO tuned and AIS based controllers for a pulse load of 3.6 MJ is depicted in Fig. 14 But, since no energy storage device is used in this study and the DSTATCOM has limitations in supplying active power, it is observed for this test system that the voltage dip cannot be improved further with the application of DSTATCOM if a realistic pulse load of 6 MJ or above is applied. But, the DSTATCOM can damp out the post pulse load oscillations quickly by controlling the reactive power injection. The role of DSTATCOM in controlling the voltage dip as well as the post disturbance oscillation can also be prominently observed if the load contains certain amount of reactive power. Hence, some futuristic scenarios of pulse loads containing a large amount of reactive power are also studied to observe the performance of the AIS based control strategy in worst hypothetical cases.

2. Futuristic Worst Case Scenarios: The performance of the controller is first studied with a moderate disturbance which is close to the disturbance at which the controller is tuned using PSO (innate performance). Fig. 17 compares the performance of a PSO tuned controller; an AIS based adaptive controller and a system without a DSTATCOM for the pulse loads of magnitude 20 MW/30 MVAR and having durations of 200 ms. It is again observed that both PSO tuned controller and the AIS based controller are able to stabilize the PCC bus voltage after the withdrawal of the pulse load without any significant overshoot. Whereas the system without DSTATCOM has a large overshoot when the pulse load is withdrawn.

Also, the voltage dip is minimized with PSO and AIS based controllers as compared to the system without DSTATCOM. For this moderate disturbance, the AIS based controller is superior than the PSO tuned controller only in terms of the voltage dip, which is least with the AIS based controller. Now, a severe pulse load disturbance of magnitude 20 MW/40 MVAR and duration of 300 ms is applied to the test system. Fig. 18 compares the performances of PSO and AIS based controllers and the system without DSTATCOM. It is observed that as the severity of the pulse load is increased, the action of AIS based adaptive controller has become more significant. In Fig. 18, it is clearly observed that even the PSO tuned controller produces an overshoot, whereas the AIS based controller does not. Also the voltage dip is less with the AIS based control strategy.

IV. CONCLUSION

An adaptive control strategy for a DSTATCOM based on artificial immune system has been presented. Innate immunity to common disturbances is achieved using a controller whose optimal parameters are determined by particle swarm optimization algorithm. For unknown, random and severe disturbances, adaptive immunity is developed based on immune feedback principles. The performance of the proposed controller is validated through both MATLAB and real-time implementations. The results show that the voltage regulation at the point of common coupling is much better with a properly tuned DSTATCOM. Also, it is evident from the two types of case studies, one representing the realistic pulse loads and the other representing some hypothetical worst case scenarios, 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 pulse loads. The beauty of the proposed adaptive controller is that the original optimal controller parameters are restored as the system returns to normality. This is unique for a controller that is adaptive. Such as an adaptive controller has potential for effective control of power electronics devices operating in nonlinear environments. Future study on implementing the AIS control strategy on a physical DSTATCOM hardware and validating the effectiveness of the controller on an electric ship power system remains to be investigated. The adaptive AIS control strategy presented in this paper has potential for applications in the smart power grid environment where there are possibilities of unforeseen energy and load fluctuations.

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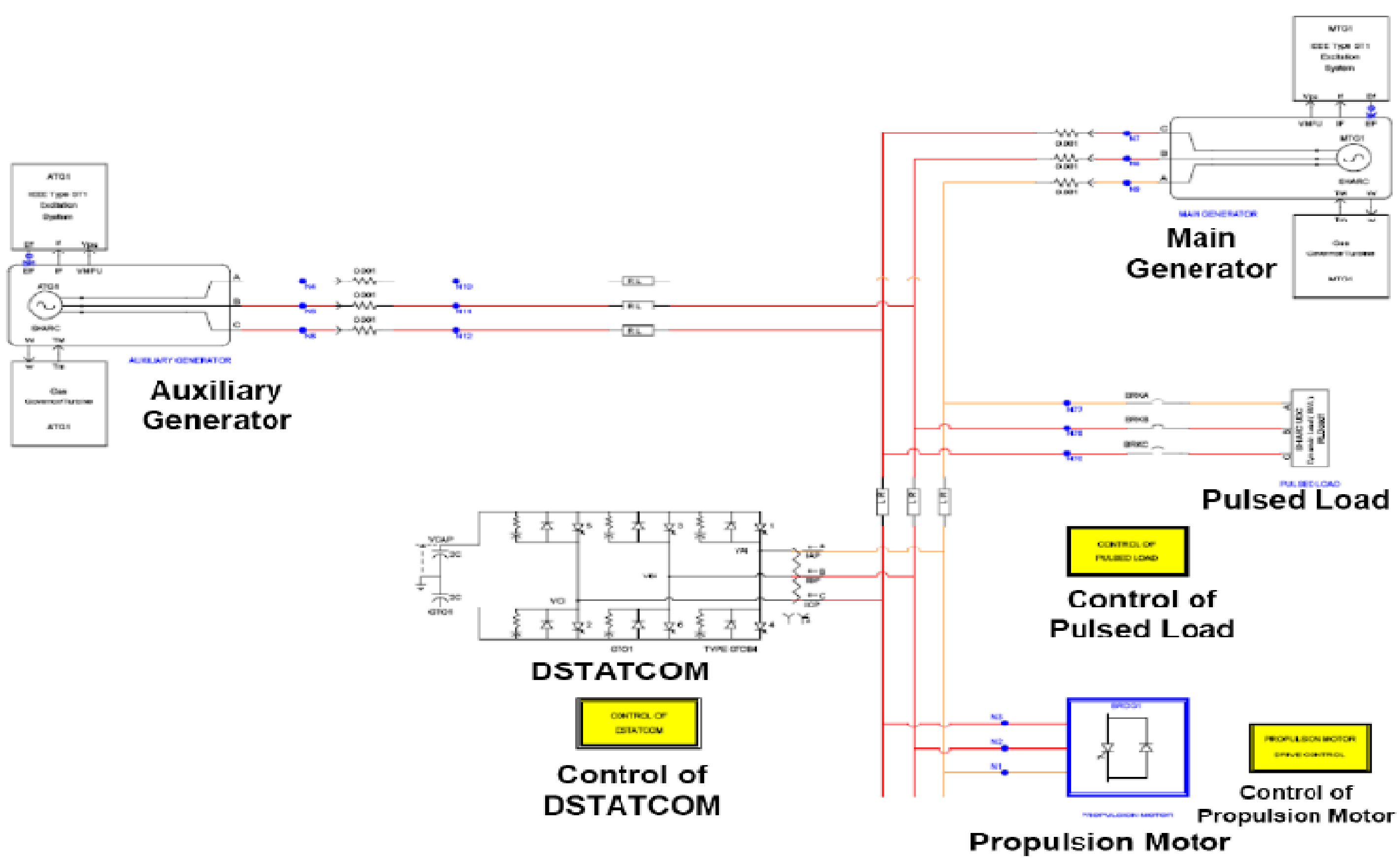

Main Generator
Auxiliary Generator
Pulsed Load
Control of Pulsed Load
DSTATCOM
Control of DSTATCOM
Control of Propulsion Motor
Propulsion Motor