An Adaptive Control Strategy for DSTATCOM Applications in an Electric Ship Power System

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***Abstract*—Distribution static compensator (DSTATCOM) is a shunt compensation device that is generally used to solve power quality problems in distribution systems. In an all-electric ship power system, power quality issues arise due to high-energy demand loads such as pulse loads. This paper presents the application of a DSTATCOM to improve the power quality in a ship power system during and after pulse 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 presented in this paper. The optimal parameters of the controller are first obtained by 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 first investigated in MATLAB-/Simulink-based simulation platform. It is verified through a real-time ship power system implementation on a real-time digital simulator and the control algorithm on a digital signal processor.**

***Index Terms*—Adaptive control, adaptive immunity, artificial immune system (AIS), digital signal processor (DSP), distribution static compensator (DSTATCOM), electric ship power system, innate immunity, real-time digital simulator (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], which is 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., for compensating the reactive power requirement of the load, etc. [4]. In this paper, the application of DSTATCOM to regulate voltage at the point of common coupling (PCC) is presented.

The internal controls of a DSTATCOM play a very important role in the effectiveness of the DSTATCOM in maintaining the PCC voltage during pulse loads. Most of the research in DSTATCOM has focused on topology and its applications. For example, different control strategies based on the respective multilevel inverter topologies of shunt compensators are discussed in [3] and also in [5]–[7]. A robust controller, sliding-mode control strategy, is adopted in [8] and [9]. 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 proportional–integral (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 much by the researchers. The study in [10] and [11] is based on neural networks (NNs). The PI controllers are replaced by a NN trained with the backpropagation algorithm in [10]. But, the training is carried out offline, and hence, the artificial neural network (ANN) based controller is not adaptive. An NN-based reference current generator is used in [11], 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

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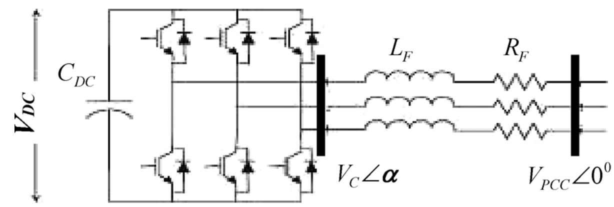

Fig. 1. Schematic diagram of DSTATCOM.

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 (PSO) 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 parameters.

The adaptive control strategy for a DSTATCOM in a shipboard power system is first investigated in the MATLAB-/ Simulink-based simulation environment [14]. Based on the satisfactory performance, it is then implemented on a platform consisting of a real-time digital simulator (RTDS) and a digital signal processor (DSP). The advantage of RTDS is that it can represent the dynamics of a system close to a practical 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 to exhibit innate response as well as the AIS-based control strategy to exhibit adaptive response are implemented on a DSP interfaced to the RTDS.

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 powers can be varied by the voltage magnitude (V_C) of the inverter, and the angle difference between the bus and the inverter output (α). The active and reactive power are expressed as follows:

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

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

where

P active power;
Q reactive power;
V_C inverter voltage;
$V_{\rm PCC}$ voltage at the PCC;
α angle of $V_{\rm PCC}$ 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 $V_{\rm PCC} < V_C$, 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, two different types of control strategies for DSTATCOM are considered.

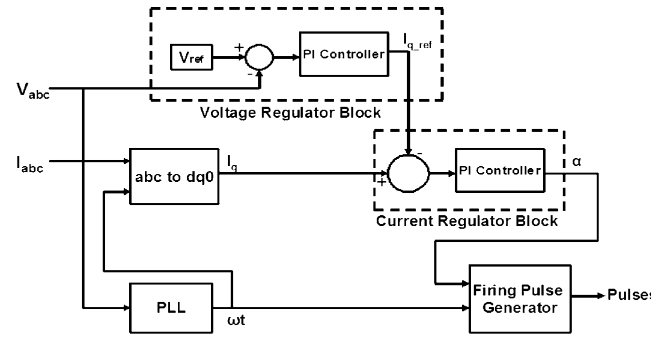

Fig. 2. Control structure for the DSTATCOM for MATLAB implementation.

The first type of control strategy is employed for the MATLAB-based simulation. Here, a gate turn-off thyristor (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 $V_{\rm dc}$ 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 $I_{q\_{\rm ref}}$. This $I_{q\_{\rm ref}}$ 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 a pulse load the bus voltage reduces to some extent, the voltage regulator changes the $I_{q\_{\rm ref}}$, 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.

The second type of control strategy consists of insulated-gate bipolar transistor (IGBT) based inverter, and is employed for the real-time implementation. It is represented in 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 $I_{d\_{\rm ref}}$ and $I_{q\_{\rm ref}}$ for the inner loop. The other two PI controllers [PI(3) and PI(4)] just keeps track of the reference.