Electric Power Systems Research 81 (2011) 1051–1059

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Integration of a bi-directional DC–DC converter model into a real-time system simulation of a shipboard medium voltage DC system

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ARTICLE INFO

Article history:
Received 15 January 2010
Received in revised form 3 November 2010
Accepted 15 December 2010
Available online 11 January 2011

Keywords:
Bi-directional dc/dc converter
Medium Voltage DC (MVDC)
Shipboard power system
Particle Swarm Optimization (PSO)

ABSTRACT

A bi-directional dc/dc converter model is investigated for a notional Medium Voltage DC (MVDC) shipboard power system to improve energy flexibility and deal with peak energy demand in shipboard power system. Surplus energy in the MVDC system during light load condition can be captured by energy storages distributed in local load zones through the bi-directional dc/dc converters and then can be used during heavy load condition or black starting of the MVDC system. In this paper, the derivation process of the small-signal average models of the isolated-type bi-directional dc/dc converter is presented for controller design. This paper also presents the controller optimization process using intelligent optimal searching algorithm, Particle Swarm Optimization, for optimizing dynamic and steady-state control performance of a bi-directional dc/dc converter. The control performance of the proposed controller is evaluated using frequency-domain analysis and time-domain simulation of the large-scale notional MVDC shipboard power system using the Real-Time Digital Simulator.

1. Introduction

Recently, direct current (dc) power distribution technology has been investigated in many studies as a promising candidate for future power systems [1–3]. The major changes in power technologies have resulted from the development of power electronic technologies. While current dc power converters are not yet comparable to ac transformers in terms of efficiency and reliability, the additional functionalities and compactness may offset these disadvantages in some applications. Considering the fact that most power electronic loads need dc power for end use or dc power interfaces, dc distribution systems are considered advantageous for both low and medium power level distribution. Moreover, since power converters can execute multiple functions including active flow control and power quality improvement concurrently, they can provide flexibility in power system control and management.

This research is targeting dc power systems in electric ships, specifically a notional U.S. Navy Medium Voltage DC (MVDC) shipboard power system. Since shipboard power systems have limited resources in limited space, its control objectives are more rigorous and strategic than terrestrial power systems with regard to protections, restoration, reliability, survivability, and so on [4,5]. The purpose of the study is to develop a notional MVDC power system for next-generation integrated electric ship. Since the MVDC system contains a lot of components such as turbine generators, power converters, energy storages, and critical loads (radar, pulsed loads, and motor drives), the major task of the Electric Ship Research and Development Consortium (ESRDC) and FSU/CAPS is to implement the whole MVDC system into a real-time simulation model considering hardware-in-the-loop (HIL) test. Therefore, the final product of the whole project is the real-time simulation model in the RTDS (Real-Time Digital Simulator™) environment. From this point of view, the goal of the work presented in this paper is to augment the simulation model of a notional MVDC system, developed by the ESRDC as illustrated in Fig. 1, with realistic bi-directional dc/dc converter models. With the availability of such a model in a large scale simulation model, this research subsequently focuses on improving energy efficiency of the MVDC system using bidirectional dc/dc converters.

The configuration of the developed bi-directional dc/dc converter model is depicted in Fig. 2, originally proposed by Wang et al. [6], because it has the following important features required by shipboard power systems: (1) galvanic isolation between two voltage levels through a high frequency transformer, (2) full-bridge converters on both sides for high power application, (3) current-fed converter on the low voltage side and voltage-fed converter on the high voltage side, and (4) active clamping circuit on the low voltage side for zero-voltage switching. Compared to other configurations such as those employing voltage-fed converters on both sides [7], this configuration can smooth the power transfer due to the induc-

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doi:10.1016/j.epsr.2010.12.010

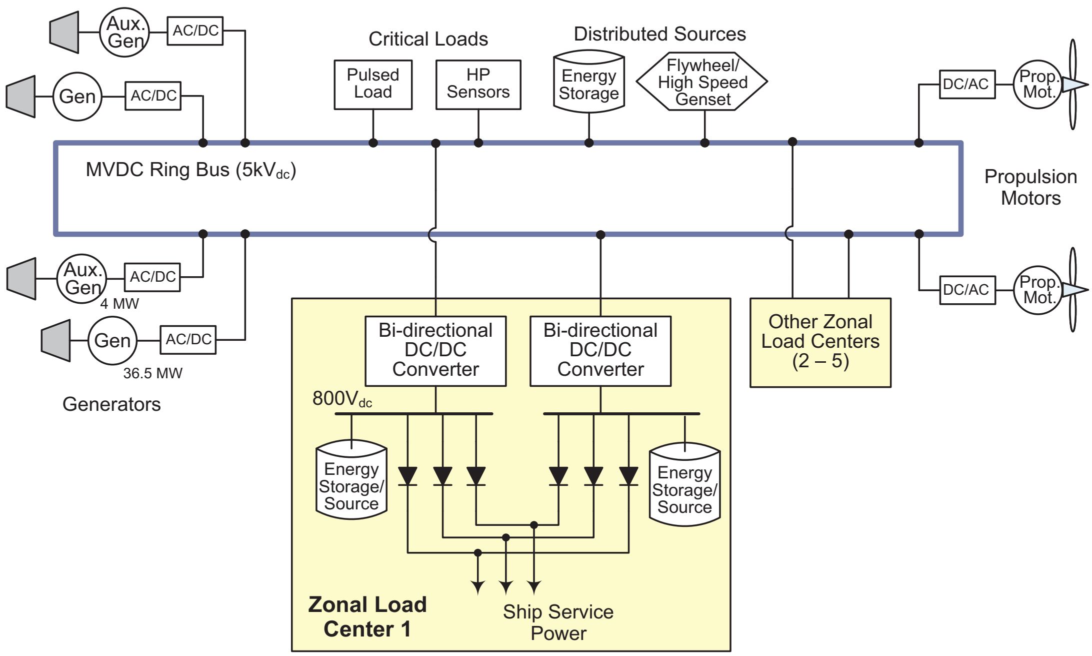

Fig. 1. Notional shipboard MVDC power system.

tor and allow the independent control of the two converters in each operating mode.

This paper presents the controller design procedures of the bi-directional dc/dc converter. In Section 2, the small-signal average models of the converter for buck mode and boost mode are derived. The small-signal average models can provide useful tools for evaluating control performance such as pole locations and stability margins. Section 3 describes controller design process of the bi-directional dc/dc converter. An intelligent optimum search algorithm referred to as Particle Swarm Optimization (PSO) is applied to optimize the controllers. Finally, the control performance is verified via frequency-domain analysis and real-time simulations of the developed large-scale shipboard MVDC system in Section 4.

2. Bi-directional DC/DC converter

2.1. Basic principle

The bi-directional dc/dc converter has two operating modes – buck and boost mode. In buck mode, electric power is transferred from the high voltage side to the low voltage side. To this end, the cross-connected switch pairs in the voltage-fed converter such as (S_5, S_6) and (S_7, S_8) should be switched in turn as shown in Fig. 3(a) where D and T_s represent the steady-state duty cycle and the switching period, respectively. During the on-time of either pair of switches, which lasts for $D{\cdot}T_s$, electric energy is transferred to the low voltage side and stored in the inductor. Then, during the dead time between the gating pulses, which lasts for $(1-D){\cdot}T_s$, the energy stored in the inductor is discharged so that the energy stored in the inductor can be balanced overall. The output capacitor (C_1) smoothes the output voltage. The current-fed converter and the active clamp circuit are turned off in buck mode and the current conducts only through the diodes.

In boost mode, power flows in the opposite direction – from the 800 V local load zone to the 5 kV MVDC bus. The current-fed converter operates as shown in Fig. 3(b) and the voltage-fed converter is off in this mode. During overlapping period, when all the switches of the current-fed converter are on, electric energy supplied by the local load zone is stored in the inductor. When one pair of the switches is turned off, the current starts flowing through

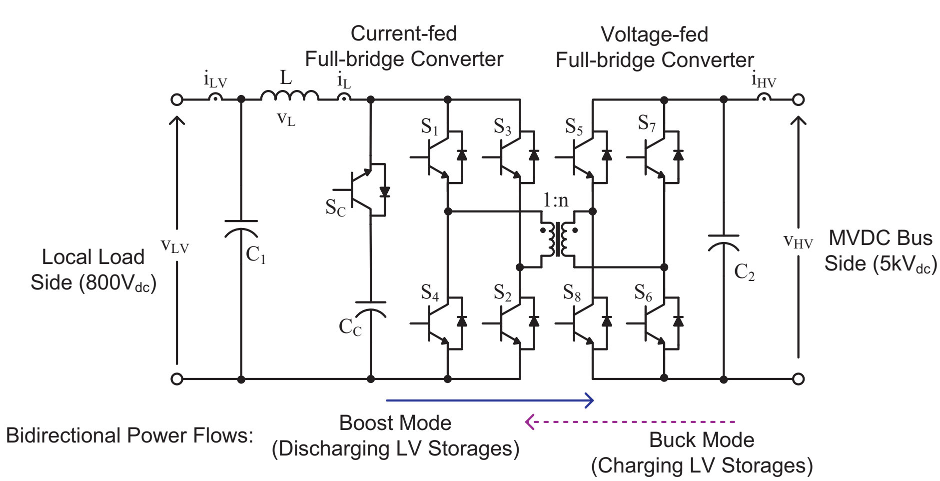

Fig. 2. Circuit diagram of bi-directional DC–DC Converter.