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Original Article

Fault-tolerant design approach for reliable offshore multi-megawatt variable frequency converters

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Abstract

Inverters play a key role in realizing reliable multi-megawatt power electronic converters used in offshore applications, as their failure leads to production losses and impairs safety. The performance of high power handing semiconductor devices with high speed control capabilities and redundant configurations helps in realizing a fault-tolerant design. This paper describes the reliability modeling done for an industry standard, 3-level neutral point clamped multi-megawatt inverter, the significance of semiconductor redundancy in reducing inverter failure rates, and proposes methods for achieving static and dynamic redundancy in series connected press pack type insulated gate bipolar transistors (IGBT). It is identified that, with the multi megawatt inverter having 3+2 IGBT in each half leg with dynamic redundancy incorporated, it is possible to reduce the failure rate of the inverter from 53.8% to 15% in 5 years of continuous operation. The simulation results indicate that with dynamic redundancy, it is possible to force an untriggered press pack IGBT to short circuit in <1 s, when operated with a pulse width modulation frequency of 1 kHz.

Keywords: Fault tolerant; IGBT; Inverter; Redundancy.

1. Introduction

Realizing a reliable inverter is the key requirement for multi-megawatt variable speed drives (VSD), power conversion and power conditioning systems used in offshore applications, where breakdowns are costly and time-consuming. Inverters are active elements that contribute to about 38% of the VSD failure [1]. The increase in the reported multi-megawatt inverter reliability from a mean time between failure (MTBF) of 1 year during 1980–1995 to 3.6 years in 1998 and 6.8 years in 2014, clearly indicates the impressive improvements in high-power handing semiconductor devices, digital processing based high speed control, water cooled packing technologies, electro-thermal modeling tools, redundant practices and system autonomous intelligence capabilities [2–5]. Even though prognostics and inverter health management systems helps to advance maintenance decisions, managing catastrophic failures and ensuring the inverter availability is a major challenge for inverters used in demanding applications [6,7]. The paper is organized into seven chapters. The second chapter describes the application of high capacity inverters in the offshore sector; the third chapter describes the power and control architecture of a mature typical industrial standard multi megawatt VSD; the fourth chapter details the reliability modeling done for identifying the probability of failure (PoF) for the inverter with 5 years of continuous operation; the fifth chapter describes the advantages of Insulated Gate Bipolar Transistor (IGBT) redundancy in increasing the inverter availability; and the sixth chapter describes the methods for achieving static and dynamic redundancy for realizing fault tolerant (FT) inverter configurations.

2. Applications of multi MW inverter

VSDs are used for powering thrusters in ships and offshore rigs for propulsion and dynamic positioning applications [8]. Offshore renewable energy systems including wind

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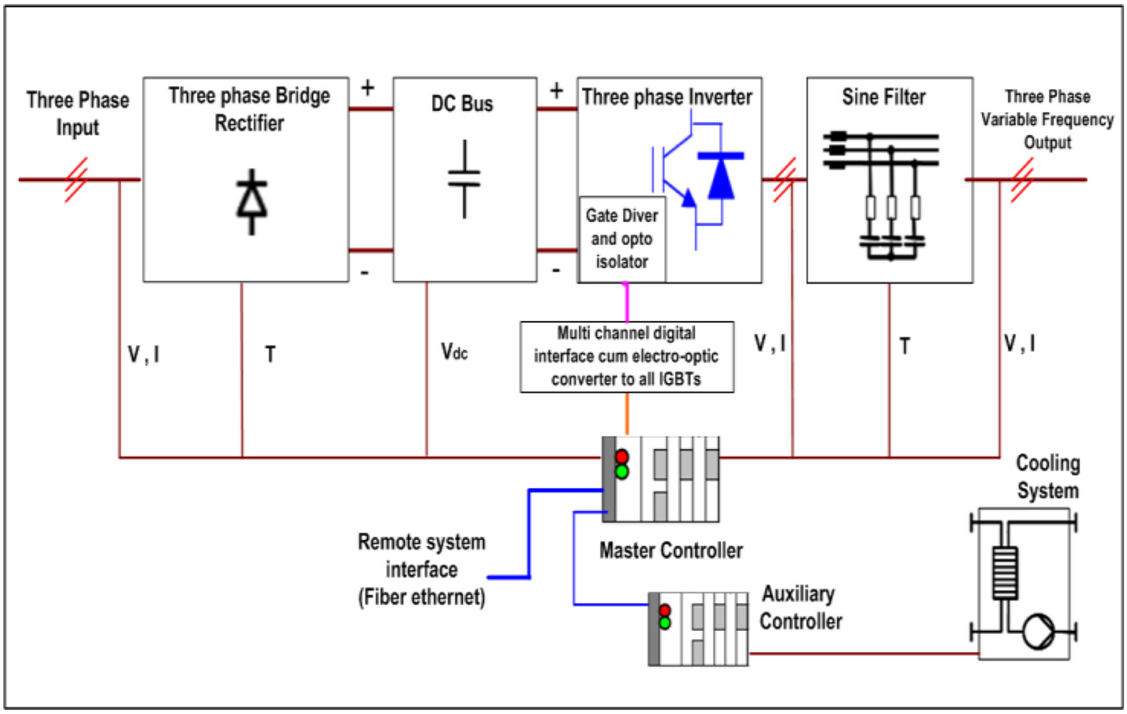

Fig. 1. Architecture of a multi megawatt VSD [7,8,18].

energy and marine current generators use inverters in the generation and grid ends, to enable efficient bidirectional real and reactive power transfer [9,10]. In the oil and gas industry, platform-based and sea bed located hydrocarbon boosting pumps and compressors are operated with VSD so as to maintain the speed required to meet to the flow requirements with declining well head pressure [11,12]. Offshore long step out flexible alternating current transmission systems (FACTS) and high voltage direct current (HVDC) systems employ semiconductor technologies for power conversion, rapid circuit switching operations, and fault limiting and interrupting devices [13]. Bulk power conversion systems require multiple inverters to be operated in series–parallel combinations [14]. Inverters with neutral point piloted (NPP) configurations and high switching frequencies are used in high speed directly motor coupled systems in subsea applications replacing unreliable gear mechanisms [15]. Inverters operated in parallel and in interlaced modes help to avoid bulky sine wave filters [16]. Active filters for harmonics mitigation use inverters operating at high frequencies for generating sinusoidal voltages [17]. Magnetic bearings used for reducing the maintenance requirements of critical subsea motors and pumps require advance information from the inverter health monitoring system for advancing their control actions [18]. Seabed conditioning trenchers, mineral mining machines and intervention systems require VSD [19,20].

3. VSD architecture and operation

The architecture of a typical industrial standard medium voltage multi megawatt VSD with IGBT-based 3-level variable source inverter is shown in Fig. 1. The subsystems include power, control, measurement and cooling sections. The power section comprises of a three phase rectifier bridge for rectifying the input alternating power supply, Direct Current (DC) bus section with a suitable combination of capacitors for conditioning the rectified DC, inverter section with IGBT for converting DC to the desired alternating frequency and a sine filter section for conditioning the output of the inverter. The control section comprises of a programmable real time controller (RTC) for computing the pulse width modulation (PWM) timings for the inverter IGBTs, and an optically isolated digital interface for transmitting the PWM signals from the RTC to the IGBT mounted gate drivers. The measurement sections comprise of transducers for measuring the voltage and current from the power sections, enabling real time control. The cooling section consists of a pump circulating deionized water through the heat sinks of the rectifier, inverters and filter systems, and an external heat exchanger. An auxiliary controller is used for managing the cooling section and other condition monitoring systems of the VSD [7,8,18].

The inverter section normally comprises of 3 IGBTs in each half leg of each phase with 6 IGBT per phase. Fig. 2 shows the power and control architecture for the top leg with IGBT, gate driver (GD) and upstream control system. Based on the inputs from the programmed control logic and measurement network, the RTC calculates the PWM pulse timings for switching the IGBTs, and sends signals in an electrical form to the optical interface circuit board. The optical interface circuit board converts the signal from the electrical to the optical format, and dispatches the optical signals to the GD of the individual IGBTs (totally 18 IGBTs with 3 per leg/phase).