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Double resonant isolated converter for battery charger with fast switching semiconductors used in hybrid electric shunting locomotive

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ABSTRACT

This paper presents the study and experimental validation of a 9 kW lead-acid battery charger used to feed the 72 V DC-Bus inside a hybrid electric locomotive demonstrator realized in the frame of the French research project PLATHEE (energy-efficient and environmentally friendly train platform). The role of the converter is to supply the 72 V DC consumers and charge the battery. The proposed topology for the battery charger is a DC/AC/DC step-down converter structure using high frequency transformer and double resonant series-parallel dipole. Main advantages of this topology are losses minimization due to soft switching operation, reduction of passive component weight and easy system integration. However, development and testing of the converter remain complex owing to high frequency constraints. Anti-parallel diodes of DC/AC half-bridge dissipate losses in excess during switching sequences and their reverse recovery energy leads to constraining high current peaks. A solution consists in using fast Insulated Gate Bipolar Transistor (IGBT)/diode technology well suited to high frequency switching, and able to limit diode peak-current amplitude during switch-off. Electro-thermal endurance tests have been performed in order to characterize the thermal behavior of the semiconductor module and control its case temperature raising. The battery charger working has been first validated on laboratory test-bench using a battery emulator, and then implemented in the hybrid locomotive for electrical couplings tests.

1. Introduction

A hybrid train is a rail vehicle that uses an on-board rechargeable energy storage system placed between the power source, often a diesel engine prime mover, and the traction transmission system connected to the wheels. The use of power electronic equipment has increased in railway vehicles. One of the solutions to improve the reliability and performance of these systems is to integrate energy storage devices into the power system network. New electric rail vehicles (locomotives) are equipped with power electronic traction chains, including energy management [1] or hybrid railway systems integrating onboard electrical energy storage technology, in particular electrochemical batteries [2]. Hybrid switcher locomotive demonstrators or railway platforms have already been designed and realized in the USA, Japan, and some of them using fuel cells and hydrogen storage on-board or integrating hybrid traction chains [3]. As an example of the application of fuel cells (FC) in the railway area, a FC hybrid locomotive is presented in [4,5]. Powered by two FC stacks which deliver a continuous power of 250 kW, the locomotive can produce a transient power up to 1 MW thanks to the hybridization. This makes the locomotive one of the heaviest and the most powerful fuel cell land vehicle. In Japan, a test running of a railway vehicle equipped with 100 kW fuel cells has been also performed [6]. The French national railways company (SNCF) and several other academic and industrial partners are involved in a research program called PLATHEE (energy-efficient and environmentally friendly train platform), started in 2006, which aims at investigating and testing energy-efficient and environmentally friendly traction systems [7,8]. The locomotive is a retrofit from a diesel one type BB63000 and has a multi-source hybrid electric traction. The traction power is 400 kW; its adherent mass is 68 tons.

More precisely, the paper scope focuses on the 9 kW battery charger which is one of the essential components of the electrical power chain. It is connected to the mid-voltage 540 VDC bus and supplies the 72 VDC battery network dedicated to the auxiliaries

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(Man Machine Interface, control command for the embedded converters, electrical actuators and sensors...). The electrical topology of the battery charger initially provided by Faiveley Transport has been modified and adapted to meet the electrical requirements of the mid-voltage DC network of the locomotive. The electrical topology that has been chosen is a DC/AC/DC step-down conversion structure based on a high frequency double resonant series-parallel circuit which allows soft switching, losses minimization, reduction of passive component weight and easy system integration. Owing to the high frequency constraints and losses dissipation, fast Insulated Gate Bipolar Transistor (IGBT) semiconductor technology is used in order to minimize diode reverse recovery energy, and improve thermal performance.

The article is organized as follow: A first part is dedicated to the battery charger topology, its design, adaptation of the electrical topology to the DC-bus of the locomotive and control of the switches. In the second part, experimental comparative results are provided for two different IGBT/diode technologies with calculation of losses dissipation. Thermal endurance tests are also performed in order to evaluate the electro-thermal behavior of the semiconductor modules. The battery charger working has been validated in laboratory, then integrated in the hybrid locomotive platform for electrical tests.

2. Battery charger electrical topology, functioning and control of IGBTs

The battery charger maintains the battery energy level, and supplies the different auxiliaries connected to the 72 VDC bus. If the 540 VDC network or the battery charger may have malfunction or failure, the battery supplies the key-auxiliaries by itself or can also provide energy autonomously in case of electrical problem to ensure the running of the locomotive for a while. Control strategy, dynamic performance of the converter and harmonic analysis for the resonant current have been presented by authors in [9].

The electrical topology of the charger is a DC/AC/DC power electronic converter inspired from indirect DC/DC isolated power electronic structures with high frequency transformer [10] and with double resonant circuit [11,12]. The structure is derived from an IGBT/Diode full bridge that was previously connected to a 300 VDC network used for light railway urban vehicle and was provided by Faiveley. The topology and IGBT devices have been adapted to meet electrical requirement of the mid-voltage locomotive network. The bridge leg composed of transistors (T2–T4) is an IGBT/Diode half-bridge. The choice of a half-bridge with 270 VDC capacitive middle point (C1–C3) permits to connect the DC/AC input stage to the 540 VDC on-board locomotive network, and sharing by two the voltage constraints on the IGBT devices. The AC part of the charger is composed of a double resonant series-parallel circuit of order 3 which allows operating in soft switching for the IGBT/Diode, and minimizing the switching losses. A 10 kVA high frequency transformer ensures galvanic isolation. Some others modifications have been made on the structure specifically on the input voltage sensor, passive input filter, electronic driver cards and software. The new and adapted general topology that has been tested and implemented in the locomotive is shown in Fig. 1(a). IGBT/Diode half-bridge (T2, T4) with filtering capacitor C used for the first stage DC/AC is detailed in Fig. 1(b).

The double resonant circuit is the key component of the battery charger topology. Two characteristic frequencies can be defined. The C_P–L_P cell creates the antiresonant frequency (F_{min} = 20 kHz). If the half bridge commutates at 20 kHz, the charger does not deliver any power to the battery and auxiliaries. The charger is in the standby mode. The resonant frequency value (F_{rs} = 80 kHz)

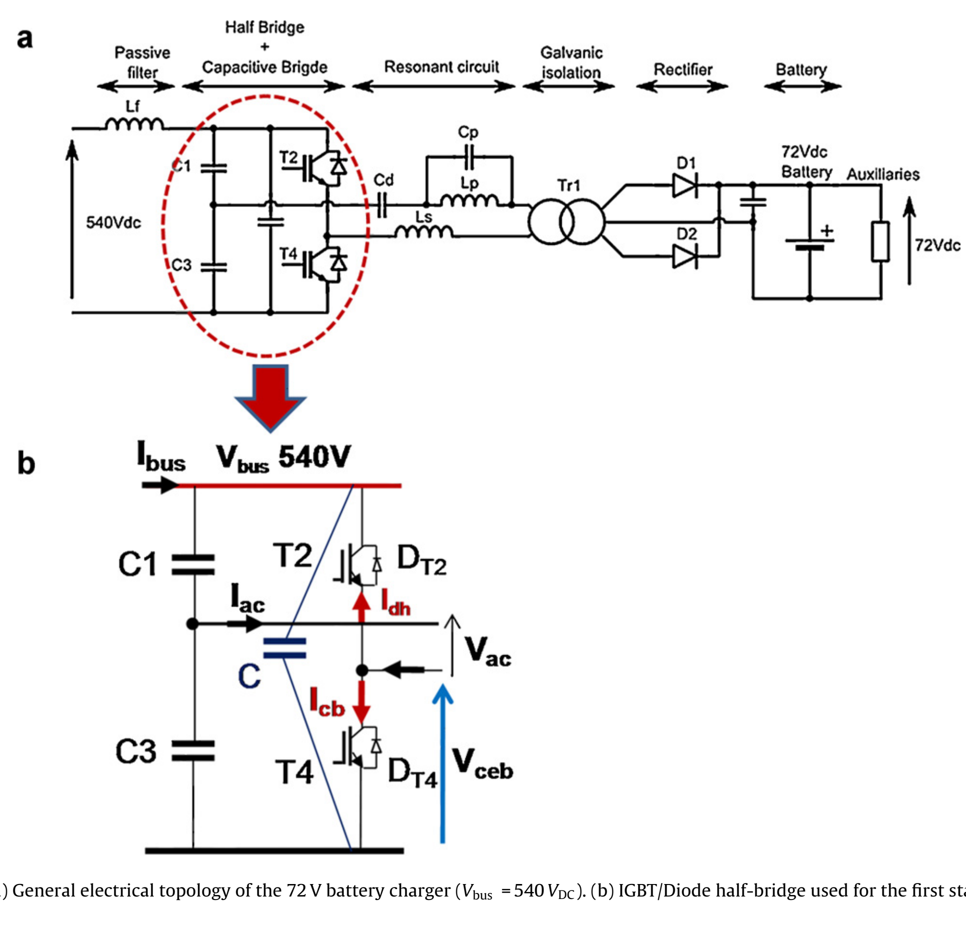

Fig. 1. (a) General electrical topology of the 72 V battery charger (V_{bus} = 540 V_{DC}). (b) IGBT/Diode half-bridge used for the first stage DC/AC.