A High Power, Current Sensorless, Bi-directional, 16-phase Interleaved, DC-DC Converter for Hybrid Vehicle Application

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***Abstract* -- A 16-phase interleaved bidirectional DC/DC converter is presented featuring smaller input/output filters, faster dynamic response and lower device stress for hybrid vehicle applications. This converter is connected between the ultracapacitor (UC) pack and the battery pack in an energy storage system of a hybrid vehicle. Typically, multi-phase interleaved converters require a current control loop in each phase to avoid current imbalance among phases. This increases system cost and control complexity. In order to minimize imbalance currents and remove the current control loop in each phase, the converter is designed to operate in the discontinuous conduction mode (DCM). The high current ripple associated with DCM operation is then alleviated by interleaving. The design, construction and testing of an experimental hardware prototype is presented, with the test results included. Finally, a novel soft switch topology for DCM operation is proposed for future research, to achieve zero-voltage switching (ZVS), or zero-current switching (ZCS) in all transitions.**

***Index Terms*— Multi-phase Interleaved DC-DC Converter; Discontinuous Conduction Mode; Ultracapacitor; Battery; Hybrid Electric Vehicle; Soft Switching.**

I. INTRODUCTION

The transition from internal combustion engine (ICE) vehicles to pure electric vehicles (EVs), or hybrid electric vehicles (HEVs) is very attractive and desirable, but there are still some serious issues in energy storage technology. The combination of batteries and ultracapacitors as an energy storage unit is considered as a potential solution to improve vehicle performance, battery lifetime and durability [1] [2]. This combination allows an excellent performance in both high acceleration and regenerative braking power. The typical topology of a battery and ultracapacitor energy storage system is shown in Fig.1. The battery pack is parallel connected with the ultracapacitor pack through a bi-directional DC/DC converter [3][4]. One objective of the design is that the converter has to achieve a high power density with low current/voltage ripple, particularly on the battery side. Moreover, the converter also has to meet prevalent automotive requirements, such as high efficiency, low cost, low EMI, and compact component size. Several different circuit topologies for high power applications have been published in [5][6][7][8][9]. A multi-phase interleaved DC/DC converter is adopted as a good solution for the application with high power and high current.

Interleaving techniques have been used widely in power converters in recent years [9][10][11][12][13][14]. Typical benefits of interleaving techniques include: reducing device stress by separating power into each discrete phase, reducing filter size by increasing effective frequency, and cancellation of the current ripple effect. The interleaving technique also enables some other beneficial technology changes, such as replacement of aluminum electrolytic or polymer organic capacitors with film or ceramic capacitors, which would improve the equivalent series resistance, power density, and reliability in a rugged thermal environment.

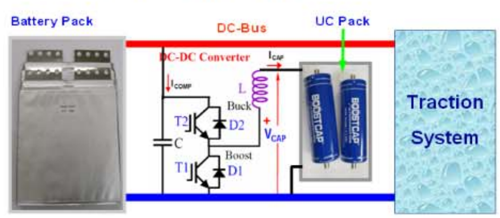

Fig.1 The typical topology of a battery and ultracapacitor energy storage system.

However, most of the published papers require a current control loop in each phase to achieve balanced phase currents and improve dynamic response [11][14][15][16]. The cost, weight, and control complexity grows when the number of phases increases, which limits the total number of phases to be considered. The optimum number of phases will be another issue that has to be considered [10][17][18]. The imbalance current mainly depends on duty cycle differences, inductance value differences, and parasitic resistance differences among different phases, all of which integrate over time in a continuous conduction mode converter. In order to minimize imbalance currents and eliminate the current control loops, some authors designed a synchronous converter working in continuous conduction mode (CCM). However, the inductor current falls to a negative value during every switching cycle [12][13], which would lead to a higher current ripple per phase and lower efficiency, especially for light load conditions.

This paper proposes the design of a 16-phase interleaved power converter operating in discontinuous conduction mode

