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A rapid cell voltage balancing scheme for supercapacitor based energy storage systems for urban rail vehicles

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ABSTRACT

Supercapacitors are widely used in energy storage systems (ESS) due to the merits including high power density, relatively long life cycle, and fast charging/discharging capability. Recently, it is becoming possible to use supercapacitor based ESS as the single energy source to power an urban rail vehicle. Cell voltage balancing control is necessary for the ESSs where supercapacitor cells are connected in series in order to have safe and reliable operations. A typical charging cycle of onboard supercapacitor stack is around 30 s. A high voltage balancing current is demanded in order to realize cell voltage balancing within the charging courses. In this paper, a new voltage balancing circuit, which is derived from an improved push–pull converter and with high current capability, is proposed for supercapacitor based ESS applications. A voltage balancing algorithm based on predicted cell behaviors is proposed to shorten the cell balancing time and improve the cell balancing efficiency. Simulation and experimental results are provided to verify the effectiveness and advantages of the proposed cell voltage balancing system.

1. Introduction

Supercapacitors have been widely used in public transportation systems due to its advantages in terms of high power density, long lifetime, fast charging and discharging capability, and fast response [1–3]. With the development of ESS, supercapacitor based ESSs can be used as the only power source for urban rail vehicles. There are a few benefits of doing this. First, the traditional power supply catenary can be omitted since the vehicle is only powered by the onboard supercapacitor stack [4,5]. Then, large amount of construction cost can be saved and the landscape along the rail can be protected. In addition, more regenerative braking energy can be absorbed by supercapacitor stacks, which boost energy conversion efficiency.

As the voltage and current provided by a supercapacitor cell is limited, large number of supercapacitor cells need to be connected in parallel and series to provide a specific voltage and current levels which are demanded by urban rail vehicle applications. However, the terminal voltage of each supercapacitor cell may diverge from each other due to unbalanced cell parameters in a series connected capacitor stack [6–8]. The voltage imbalance can cause serious consequences. Supercapacitor cells with less capacity will be overcharged and overdischarged during charging and discharging processes, which is harmful to supercapacitors and can lead to the explosion of supercapacitors in the long term [9,10]. To ensure normal operations where cell voltages are balanced, specific cell voltage balancing circuits are usually used in practical systems [11,12]. The charging time for supercapacitors is typically limited. The charging time for supercapacitor urban rail vehicles is approximately 30 s, which ensures that the vehicle can be fully charged during the vehicle parks at the platform for passengers' boarding. For example, Guangzhou Urban Rail vehicle, which is the first commercial supercapacitor urban rail vehicle in the world, the voltage of onboard supercapacitor can be charged to 750 V in 30 s [13]. It is usually required that the cell voltage balancing needs to be accomplished within the charging process. In order to achieve this, a large balancing current is demanded.

Generally, there are two types of voltage balancing circuits, which are passive voltage balancing circuits and active voltage balancing circuits. In a passive voltage balancing circuit, a resistor is connected in parallel with a supercapacitor cell to absorb the extra energy [14,15]. The realization of the passive voltage balancing circuit is simple and cheap, while with lower efficiency due to the involvement of lossy resistors. Passive voltage balancing schemes are usually used for low power applications.

In an active voltage balancing scheme, the energy is transferred among supercapacitor cells with the help of power converters. As compared with the passive circuits based approaches, higher

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efficiency can be achieved in the active voltage balancing circuits since less loss is generated by the voltage balancing circuits. There are three types of energy transfer modes, which are cell to cell mode [16–19], cell to stack mode [20,21] and stack to cell mode [22–24] in an active cell balancing circuit. In the cell to cell mode, energy is transferred from the cells with extra energy to the ones with least energy. In the cell to stack mode, energy is transferred from the cell with the highest energy to the whole stack. In the stack to cell mode, energy is transferred from the whole stack to the single cell with least energy. There are trade-offs with different energy transfer modes. In the cell to cell mode, the voltage balancing current is small. The energy transfer path is long and the voltage balancing process is slow when the number of cells is large, which is not suitable for the onboard supercapacitor applications. In the cell to stack mode, the voltage and current stresses of supercapacitor cells are reduced, which is suitable for high power applications. However, the voltage balancing current from a single cell is limited, which is not appropriate for fast charging applications. The stack-to-cell mode is more suitable for voltage balancing of onboard supercapacitors since high balancing current can be provided [25].

As we discussed above, the cell voltage balancing needs to be finished within a short time. Thus a high cell balancing current is required. In this paper, a voltage balancing circuit is proposed for fast cell voltage balancing applications, which is shown in Fig. 1. Essentially, the proposed circuit is an isolated dc/dc converter with multiple outputs. Each output is connected to one supercapacitor cell. The input of the circuit is connected to the terminals of the cell stack. A multi-winding transformer is utilized to provide energy transfer paths among cells. The primary side of the transformer is a push–pull circuit with a clamping capacitor. The clamping capacitor is added to absorb the voltage spikes across the switches for more efficient power flow. The addition of the clamping capacitor enables the proposed circuit to provide twice of the current as in conventional push–pull converter.

The secondary side of the transformer is connected to series-connected cells through corresponding synchronous rectifiers. In practical applications, the number of cells is typically very large. It is difficult to design too many secondary windings in a single transformer. The modular design method can be applied to overcome the difficulty, where cells are categorized into different modules. The voltage equalization within a module can be realized by the scheme proposed in Fig. 1. The inter-module voltage equalization can be achieved similarly by designing a new multi-winding transformer which supplies a secondary winding to the corresponding module.

In order to enhance the performance of the cell voltage balancing performance, a new cell balancing control algorithm based on the predicted cell behavior is proposed. In conventional cell voltage balancing algorithms, energy is transferred back and forth among different cells. The instantaneous cell information is used to determine the energy transfer directions. However, the energy transfer is based on the predicted cell behavior in the proposed algorithm, and

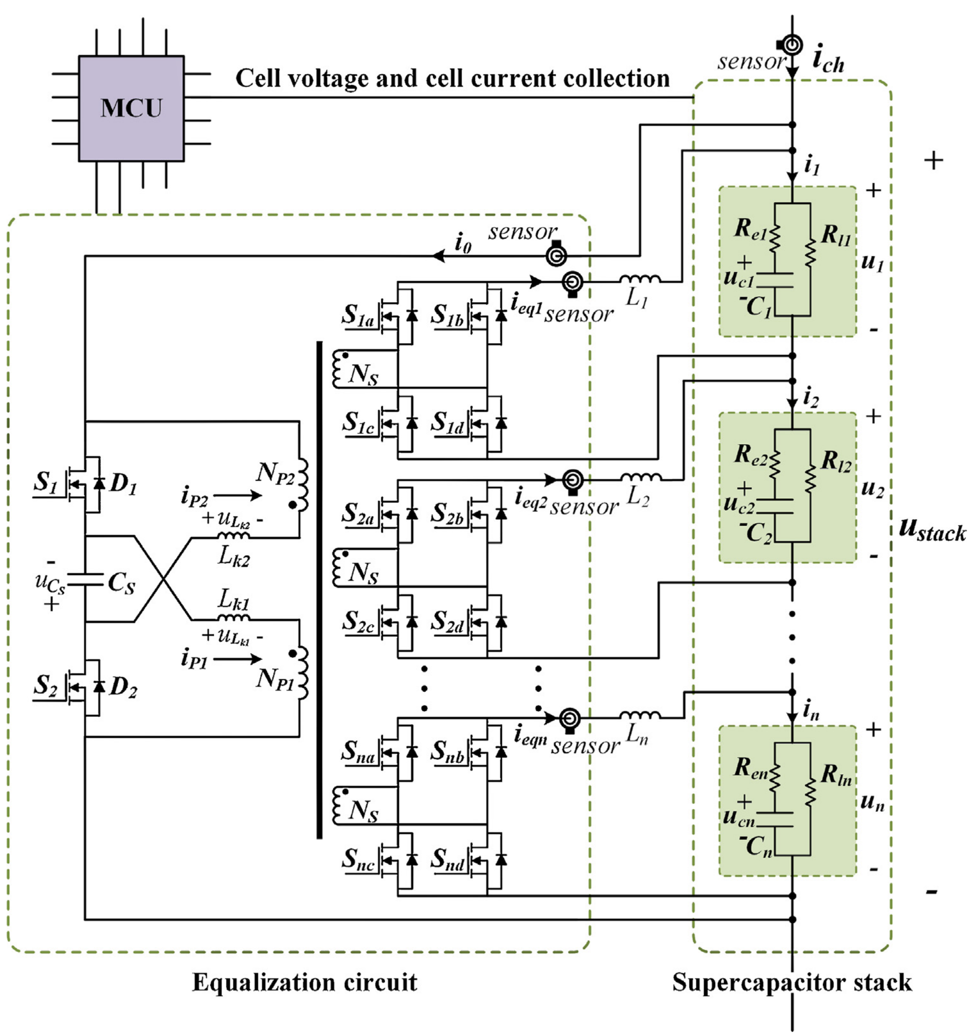

Fig. 1. Proposed cell voltage balancing scheme.