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INVESTIGATION OF MULTIPHASE MODULAR TOPOLOGY FOR ENERGY STORAGE SYSTEM

Dimitar Arnaudov*, Stoyan Vuchev

Technical University of Sofia, Bulgaria

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ABSTRACT

The paper presents a modular system for charging of energy storage elements. Characteristics of the topology are obtained for variation of different circuit components values. In accordance with the obtained results from the parametric analyses, recommendations for the choice of components for the individual modules are discussed. The system operability with fault condition in one of the modules is investigated. Options for simultaneous operation of the modules to a common load are presented. The use of synchronous converters for efficiency optimization purposes is examined.

INTRODUCTION

Modular converter topologies with increased output power capabilities and optimized parameters [1, 2, 3] are often implemented in systems for energy storage applications. By the use of current-driven resonant converters with improved efficiency [4, 5], different operating modes can be obtained throughout the process of charging. Increasing the number of stages operating in parallel to the common load, both flexibility and reliability of the system is guaranteed.

The increased complexity, however, may have negative effects on the overall topology behavior due to tolerances of the circuit components and interaction between the individual modules. As a result, asymmetry in the converter system operation may occur [5], which may have a further influence on both the performance and the output parameters.

The following paper presents results from examination of a modular topology for charging applications. The interaction between the individual modules is examined. Options for control of the output current value are discussed. Based on a developed model of the system in LTspice, parametric analyses are performed in order to investigate the influence of the circuit tolerances on the overall topology operation. The converter behavior with the occurrence of a fault condition in one of the stages is analyzed.

EXAMINED CONVERTER TOPOLOGY

Block diagram of the investigated topology is presented in Fig. 1. The converter system consists of N number of identical modules realized on the base of a controllable input rectifier, a resonant inverter and an output rectifier. In order to obtain balanced topology operation and to reduce the output current ripple, the modules are phase shifted at an angle of 360/N degrees between each other.

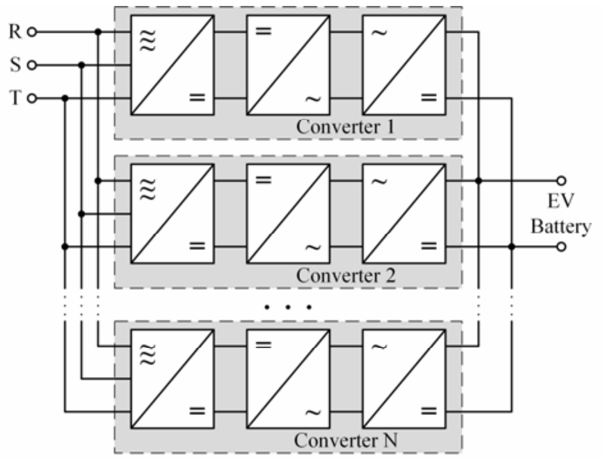

Fig. 1. Block diagram of the examined converter topology.

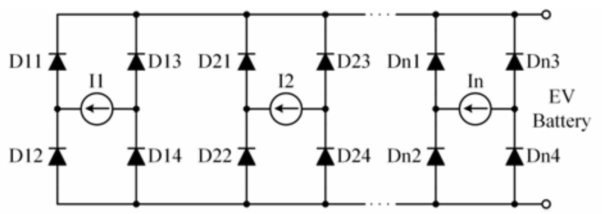

Fig. 2. Circuit of the examined converter topology

Fig. 2 presents the circuit of the examined converter. Single-phase diode bridges connected in parallel are used for realization of the modules output rectifiers. The individual topology stages are based on half-bridge series resonant inverters with voltage limitation applied to part of the resonant tank capacitor [6]. In Fig. 2, these inverters are represented by ideal sources of current in accordance with

* Corresponding author. E-mail: dda@tu-sofia.bg

their behavior during operation. The operation of the current-driven bridge rectifiers is presented in [7].

MODELLING AND INVESTIGATION OF THE MODULAR TOPOLOGY

A detailed model of the examined converter system is developed in the software environment of LTspice with respect to the presented in Fig. 1 and Fig. 2 circuits. In order to optimize the computer simulations, the input rectifiers are substituted with ideal DC voltage sources with a nominal value of 30V. The energy storage element (ESE) is represented by a series RC-load. Thus, load behavior of a supercapacitor bank with parasitic resistance (including the wire connections) is obtained. The capacity is significantly reduced in order to optimize the time of the simulation process. The supercapacitor bank is not initially charged.

The circuit of the resonant inverter stages is presented in [6]. Full models of these modules are implemented, including ideal high-frequency transformers with a unity ratio for realization of galvanic isolation between the load and the power supply grid. The switching frequency of the resonant inverters is 100kHz.

The operation of a single module during charging of the ESE is examined. Fig. 3 presents waveforms of the output current. Full sine-wave current rectification can be observed.

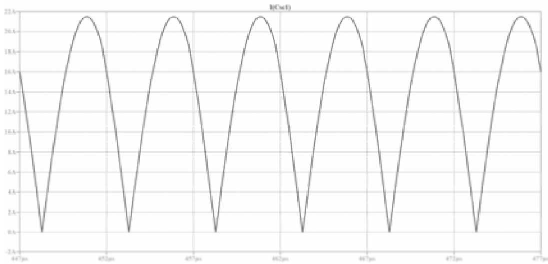

Fig. 3. Output current waveforms of 1 individual module

The average output current value of the module depends on the value of the power supply voltage of the resonant inverter stage. Fig. 4 illustrates this dependence. The presented values are normalized with respect to the nominal supply voltage and the corresponding nominal average output current.

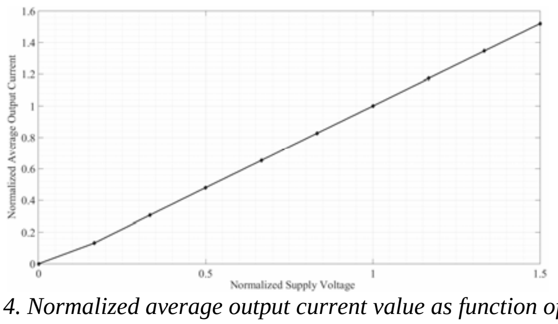

Fig. 4. Normalized average output current value as function of the normalized supply voltage (1 module)

A very good linearity of the presented in Fig. 4 characteristics is observed, which favors the supply voltage to be used as a direct control parameter. Moreover, with the use of individual controllable input rectifiers, the output current value of each module can be separately adjusted. This allows balancing of the whole topology operation.

The small non-linearity observed for low values of the supply voltage occurs when the anti-emf voltage applied to the module output has a value close to that of the supply. In a non-ideal converter system like the examined one, the resultant output voltage also includes the parasitic voltage drop of the connection wiring which may vary with respect to the ripple of the output current.

Simulation investigation of the converter operation with 3 and 5 stages connected parallel to the common load is performed. Fig. 5 and Fig. 6 present waveforms of the total charging current.

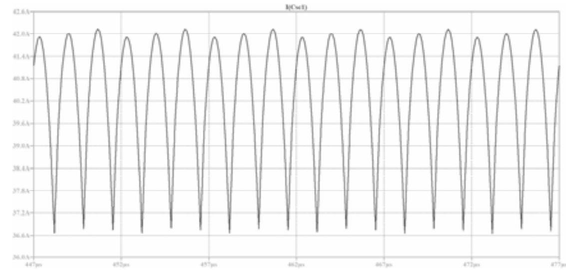

Fig. 5. Output current waveforms of topology with 3 modules (balanced operation)

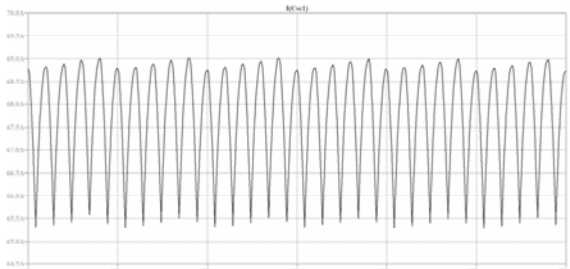

Fig. 6. Output current waveforms of topology with 5 modules (balanced operation)

From the presented waveforms, it can be seen that the different number of modules has an influence on both the output current value and the resultant current ripple (peak-to-peak value and frequency). Slight asymmetry in the topology operation may occur due to the parasitic components of the load and the connections as the momentary anti-emf voltage applied to the modules depends on the voltage drops.

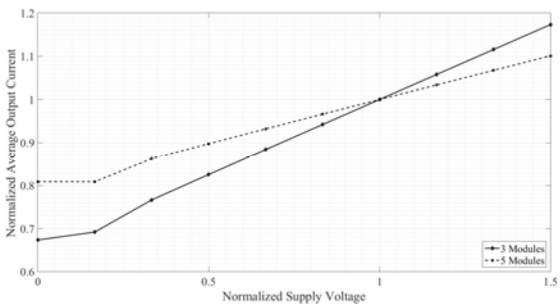

Fig. 7. Normalized average output current value as function of the normalized supply voltage of 1 module

The supply voltage of the inverter stages can be used as a control parameter. Fig. 7 presents control characteristics of the topology resultant average output current. Again, the values are normalized with respect to the nominal.

Good linearity of the presented in Fig. 7 characteristics is observed. Moreover, it can be seen that each stage contributes with 1/N of the resultant output current (33% for three modules, 20% for 5 modules).

The variation of only one of the inverters supply voltages, however, has an influence on the resultant output current ripple of the converter system. Fig. 8 presents results from simulation investigation of the total current ripple when one of the supply voltages is varied. The voltage sources for the remaining modules preserve their nominal values.

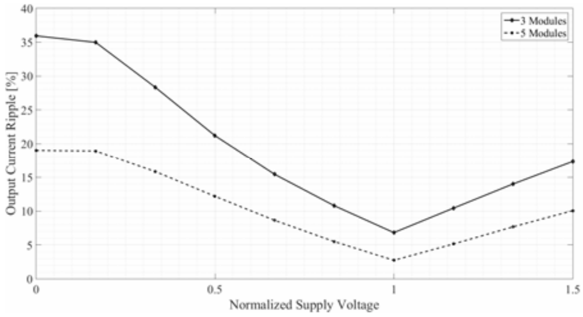

Fig. 8. Output current ripple as function of the normalized supply voltage of 1 module

From the presented in Fig. 8 results, it can be seen that the total output current ripple is reduced with balanced system operation. Moreover, significant reduction can also be obtained by increasing the total number of parallel modules - ripple values of about 7% for three parallel stages and about 3% for five stages are obtained for the nominal supply voltage values.

INTERACTIONS BETWEEN THE INDIVIDUAL CONVERTER MODULES

From Fig. 7 and Fig. 8, it can be seen that the operation of the individual module has a negligibly small effect on the other stages. In order to examine the interactions between the separate converter modules, parametric simulation analyses are performed considering the tolerances of the circuit components. Fig. 9 and Fig. 10 present transistor current waveforms from the parallel operation of three modules (5 waveforms presented in each plot).

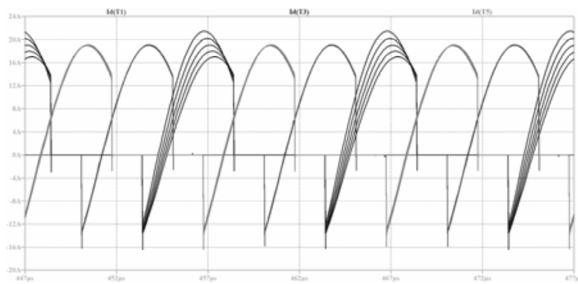
Fig. 9. Waveforms of the 3 modules transistors currents for variation of the resonant tank parameters in one of the modules within the range of ±20%

The presented in Fig. 9 waveforms correspond to ±20% variation in both of the resonant tank inductor and capacitor values for one of the inverters. The variation step of the parametric analysis is 10% of the corresponding component parameter nominal value. The inductor and the capacitor values are varied with preservation of the resultant self-resonant frequency. The other stages components preserve their nominal values.

The presented in Fig. 10 waveforms correspond to a ±20% variation in only the resonant tank inductance of one of the inverters. The variation step of the parametric analysis is 10% of the corresponding component parameter nominal value. Thus, the resultant self-resonant frequency of this module does not remain intact. The other stages components preserve their nominal values.

In both cases, the intact converter modules preserve their nominal operation, which demonstrates the very weak interaction between the individual stages.

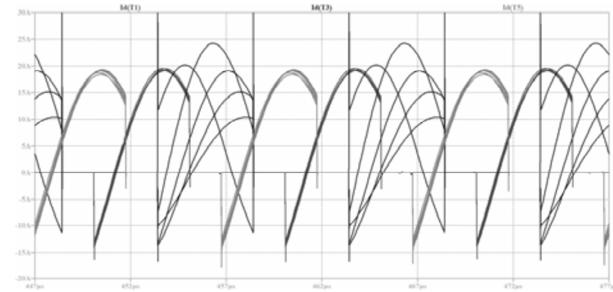
Fig. 10. Waveforms of the 3 modules transistors currents for variation of the resonant tank inductor in one of the modules within the range of ±20%

Operation of the converter system is possible even when fault condition occurs in one of the modules. Fig. 11 and Fig. 12 present waveforms of the charging current of 3-stage and 5-stage topologies with one faulty stage. The resultant current ripple, however, drastically increases – about 36% for the 3-stage converter and about 19% for the 5-stage converter, which may not fulfil the requirements of some specific applications such as electric vehicle battery charging.

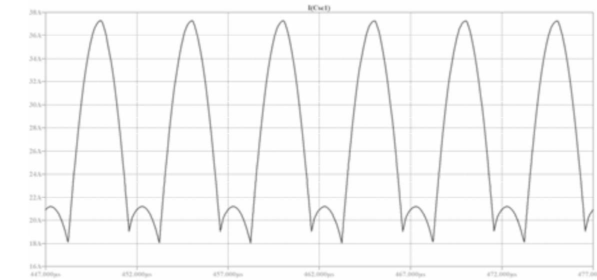
Fig. 11. Output current waveforms of topology with 3 modules (1 faulty module)

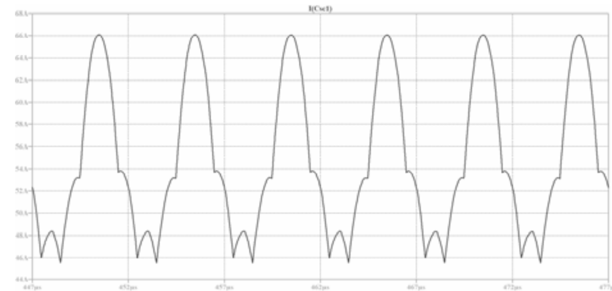
Fig. 12. Output current waveforms of topology with 5 modules (1 faulty module)

As a result of the very weak interaction between the individual modules, the reverse voltage applied to each of the output rectifiers does not practically depend on the total number of parallel stages with their different operating modes. Fig. 13 and Fig. 14 illustrate this negligible dependence within a 3-stage and a 5-stage topology respectively.

The observed ripple of the rectifier diodes reverse voltage is a result of the voltage drop across the parasitic connection resistances. In a high-voltage high-power system, such voltages drops are negligibly small compared to the anti-emf voltage of the load, especially when rechargeable battery packs are used as energy storage elements. Thus, the interaction between the operating in parallel modules can be considered negligible.

However, according to the presented investigation results, balanced system operation must be maintained in order to obtain reasonable output current ripple. In this case, methods for efficiency optimization such as the use of synchronous rectifier circuits [4] should be used instead of the asymmetric control approach. Unlike other methods for asymmetry compensation [8, 9], the examined topology provides option for balancing by direct individual adjustment of each module supply voltage.

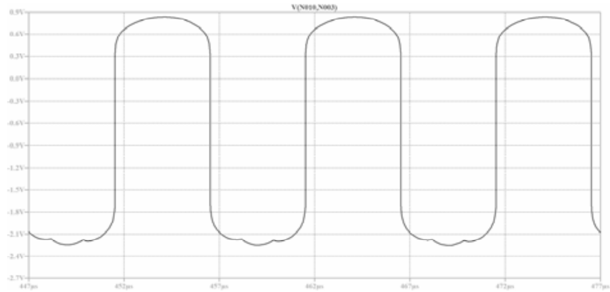

Fig. 13. Output rectifier diode voltage for topology with 3 modules (balanced operation)

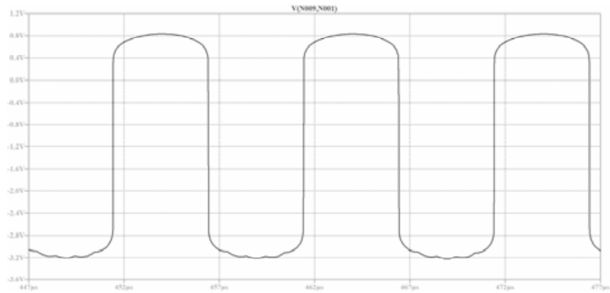

Fig. 14. Output rectifier diode voltage for topology with 5 modules (balanced operation).

CONCLUSION

The paper presents an investigation of a modular multiphase current-driven topology for charging applications. Based on the obtained simulation results, considerations about the whole converter system operation and the interaction between the individual modules are made.

The average output current of each individual stage depends directly on its supply voltage. According to the obtained characteristics, this dependence can be considered as linear, which favors the use of the supply voltage as a control parameter. Moreover, using separate input rectifiers allows fine balancing of the topology operation, which results in optimization of the charging current ripple.

Furthermore, as the total output current of the system is a sum of the individual stages output currents, one module can be used for fine adjustment of the charging current value while the other topology modules operate at the nominal mode in order to improve the overall converter efficiency. The obtained control characteristics in this case can also be considered as linear. However, such operation results in significant output current ripple.

By increasing the number of modules, the total charging current ripple can be optimized. Ripple values of about 7% for three parallel stages and about 3% for five stages are obtained for nominal operation, which results in significant optimization of the topology output filter if such is necessary.

According to the performed parametric analyses, the variation in the operating mode of one of the modules has negligible effect on the others.

The overall converter system remains functional even when a fault condition occurs in one of the stages. However, the resultant charging current ripple (over 35% for 3 modules and about 20% for 5 modules) should be furtherly considered with respect to the particular charging application requirements.

The negligible interaction between the individual parallel stages allows modules to be easily added in order to increase the total output power of the topology. Moreover, the reverse voltage applied to the output rectifiers depends only on the anti-emf voltage of the charged ESE.

ACKNOWLEDGEMENT

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