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FIELD OF SCIENCE: ENGINEERING AND TECHNOLOGY

SCIENTIFIC DISCIPLINE: AUTOMATION, ELECTRONICS, ELECTRICAL ENGINEERING AND SPACE TECHNOLOGIES

SUMMARY OF DOCTORAL THESIS

Switched capacitor resonant converter for control of voltage sharing on series-connected capacitors

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AUTOREFERAT ROZPRAWY DOKTORSKIEJ

Przekształtnik rezonansowy z przełączanym kondensatorem do kontroli napięć w gałęzi szeregowo połączonych kondensatorów

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Introduction

For many years, there has been a significant growth of interest in alternative energy sources such as sun, wind, and geothermal heat. Together with the technological progress of semiconductor devices, this has caused the rapid development of various power electronics systems for energy conversion. The multilevel neutral-point-clamped inverters are one of these research topics. This topology provides an efficient DC-AC energy conversion and enables passive circuit components such as output filters to be minimized. In case of three-level converters, NPC-based solutions are well established. However, an increased number of voltage levels in the NPC-based converter creates an important issue with its operation due to a DC-link voltages imbalance. The problem of voltage imbalance also exists in capacitors and batteries banks with series connected devices. Based on a review of the research that has been published on the matter of voltage equalization in banks of series-connected capacitors and battery cells, this dissertation provides a novel topology: Switched Capacitor Active Balancing Converter (SCABC) and control methods for active voltage equalization in a branch composed of series connected capacitors or batteries. Control methods of the proposed converters allow for its effective applications to improve operation of four-level NPC-type converters.

Aim and scope of the dissertation

The objective of the dissertation was to conduct research on the Switched Capacitor Active Balancing Converter: the principle of its operation, the applicable control algorithms, and applicability as a subpart of a modular power conversion system were investigated. The mathematical equations for the circuit description are presented and provide information about components` sizing and power losses. The topology was verified for its ability to balance the voltage on three series-connected capacitors. A control system was developed, and an experimental setup was built to prove the concept. The improved SCABC was applied in front of a seven-level NPC inverter and was able to balance its DC-link voltages efficiently. This protected the NPC inverter against an imbalanced state. The simulation results are also presented. Furthermore, the concept went beyond the active balancing. The analysed converter permitted some useful functions that are associated with energy conversion to be identified. The SCABC in an adequate configuration and with the adapted control algorithm was verified to perform the following operations:

1. Stepping up the input voltage in front of an NPC inverter that was composed of four-level legs. This eliminates the requirement for using a DC-DC boost converter in a conversion system.
2. DC-link voltage balancing in a circuit that was composed of three series-connected capacitors.
3. Decoupling a DC source power in a DC-AC system with a four-level NPC inverter. The case was verified *via* simulations. An improved control method for mitigating the double grid frequency component in a DC energy source was developed. The simulation and experimental results are presented.

Theses that have been propounded:

1. The proposed switched capacitor converter is able to successfully equalise voltages on three series-connected capacitors
2. The proposed switched capacitor converter can operate as the front converter of the multilevel NPC inverter, thereby providing balanced DC-link voltages and a reduced AC component of the supply current.

Detailed objectives of the research conducted:

1. To review and analyse the topologies that have been developed for controlling the voltage of series-connected capacitors and energy cells.
2. To develop and analyse an SCABC: its operating principle, operation modes, and the basis of the control.
3. To develop simulation models and investigate them in selected operation modes.
4. To develop the control algorithms as well as to select circuit components for an SCABC experimental device.
5. To design and develop an experimental setup for selected configurations of an SCABC with an NPC inverter.
6. To conduct the experimental research using the setup that was developed.

Research description

Chapters 1-4:

The dissertation provides a review of the research that has been published on the matter of voltage equalization using banks of series-connected capacitors and battery cells. Additionally, a novel topology is described in the thesis that is of a resonant switched capacitor type. The principle of the operation of the switched capacitor active balancing circuit (SCABC) is also presented here. The work presents the mathematical expressions for the dependencies of a circuit. The possible operation modes of the converter are presented, together with an approach for its design in terms of the required components, sizing, and ratings. The sources of a circuit`s power losses are elaborated, and its efficiency is described using equations. Moreover, the basis of the converter control is described as well. In order to prove the proposed converter concept, a simulation model in MATLAB®/Simulink® was developed. Moreover, the approach to designing the experimental setup is described and the setup that was built is presented. The results that were recorded reveal the circuit`s imperfections, and therefore, the author proposes improvements of the topology.

Chapters 5-6:

The further research that is presented focuses on the ability of SCABC to control the voltages of the capacitive voltage divider, which forms the DC-link for the seven-level NPC inverter. Two cases of the connection of the DC power supply were investigated. In the first case, a complete DC-link was supplied and the operation of the balancer was controlled by closed-loop control system. Simulations of various scenarios were performed and the results are presented. In the second case, only the middle capacitor of the DC-link was supplied, and therefore, the balancer not only maintained the voltage balance, but also boosted the supply voltage threefold. This case was studied via simulations of the circuit, as well as via laboratory experiments. Details of the development of the laboratory setup are presented as well. The results that were recorded for both cases are given. Moreover, the efficiency of a circuit was also investigated. The final goal of this dissertation was to investigate the capability of SCABC to compensate the ripple second harmonic power, which propagates to the DC part of the subsystem. The focus of the research that was undertaken was on developing dedicated control algorithms for two possible configurations of a power conversion system: an SCABC with a seven-level NPC inverter and an SCABC with a five-level NPC inverter.

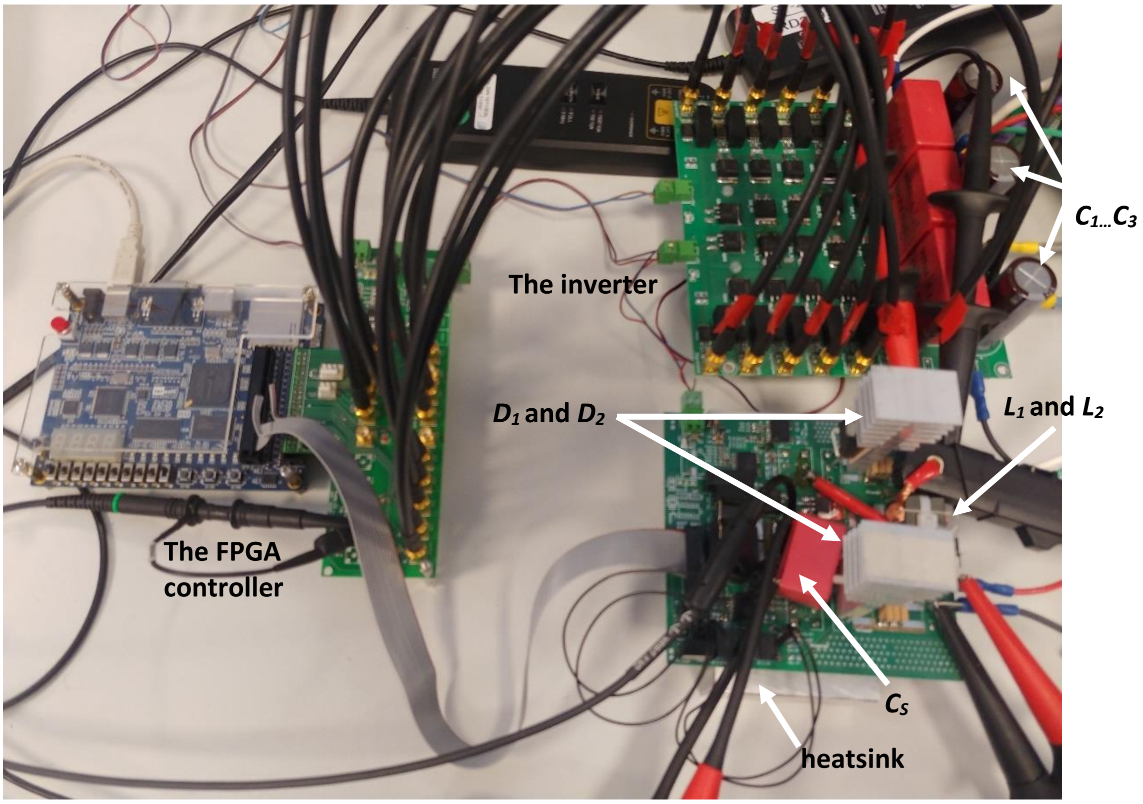

Figure 1: The SCABC and NPC inverter experimental system with a Cyclone III FPGA controller.

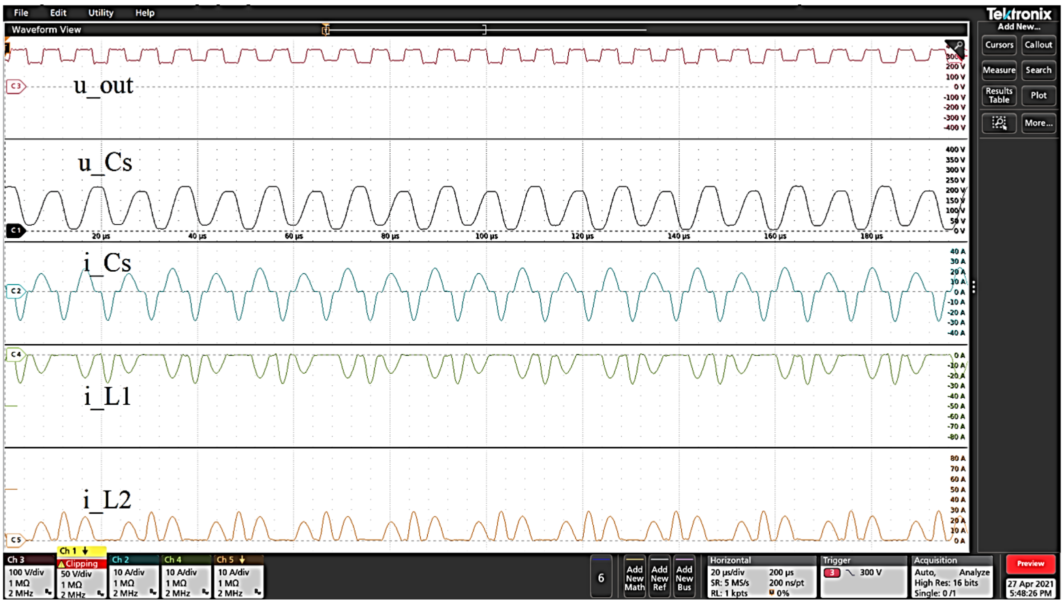

Figure 2: Operation of the balancer in the boosting mode for supplying the NPC inverter. The waveforms of the output voltage of the inverter (100[V/div]), the voltage and current of the switched capacitor (50[V/div], 10[A/div]) as well as the currents of the resonant chokes (10[A/div]; 20 µs/div

Summary

In the dissertation the Switched Capacitor Active Balancing Converter is presented. The proposed topology successfully transferred the energy between the selected capacitors in the balanced series bank through the balancing resonant branch, which equalised their voltages. Additionally, a high-rate transfer was achieved by discharging the two capacitors of the bank simultaneously. The correct operation has been confirmed by simulation and experimental results. Moreover, the simplification of the balancer`s gate-driver circuitry that was introduced operated correctly. The bootstrapping method helped to reduce the area of the printed circuit board and reduced the complexity of the design and the number of hardware components that were required. When tied with seven-level NPC inverter with PD-PWM modulation, the SCABC controlled with the proposed algorithm successfully operated as a front converter, providing proper supply for the NPC inverter. Additionally, the balancer was successfully configured in a way in which the C_2 capacitor was supplied from the DC source, and the capacitors C_1 and C_3 were fed by the SCABC. In this manner, the supply voltage was boosted three-fold and provided the energy source for the seven-level NPC inverter. The voltages of the DC-link capacitors remained balanced also for such operation mode. With proper control method applied, the SCABC was successfully operated as a DC-link balancer with power decoupling ability for a five-level and the seven-level NPC inverter. The near to DC character of the power source current confirms the effectiveness of the control algorithm proposed by the author.

With the research that was conducted and the results that are presented, it is believed that all of the objectives of this dissertation have been met. Moreover, the theses that were propounded have been confirmed: the proposed switched capacitor converter is able to successfully equalise voltages on three series-connected capacitors. Furthermore, it can operate as the front converter of the multilevel NPC inverter, thereby providing balanced DC-link voltages and a reduced AC component of the supply current.

The author’s major achievements that are included in the dissertation are:

1. Analysis of the newly introduced topology, investigating quality of its waveforms and possible applications as a standalone converter or as a subpart of a complex power conversion system.

2. Analysis of a components` load of the proposed circuit and deriving the formulas for sizing those as a function of assumed operation quantities: output power, input voltage, and switching frequency.
3. Analysis and mathematical description of power losses and efficiency for the proposed switched capacitor converter topology.
4. Designing and developing the control algorithms presented in the dissertation, which cover multiple operation modes of an SCABC and include:
    a. solving the problem of decision making on ongoing switching strategy
    b. adjusting to the conditions of variable power in the systems with DC-AC converters
    c. synchronization with AC output and elimination of the double frequency ripple
    d. Switching strategy for the bootstrap type gate supply
5. Hardware implementation of the control algorithms
6. Designing, assembling, and commissioning the experimental setups that were investigated during the research conducted.

List of publications

1. Hachlowski Jakub, Stala Robert. "A Novel Converter for Voltage Balance in Series-Connected Capacitors and Batteries"; Power Electronics and Drives 2018;3 (38):65–74
2. Hachlowski, Jakub and Robert Stala. "DC-link Voltage Balancing Converter with Resonant Switched-Capacitor Circuit for Four-Level and Six-Level NPC Inverter." 2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe) (2019): P.1-P.10.
3. Stala, R.; Hachlowski, J.; Penczek, A. NPC Seven-Level Single-Phase Inverter with DC-Link Voltage Balancing, Input Voltage Boosting, and AC Power Decoupling. Energies 2022, 15(10), 3729;
4. Patent applications at The Patent Office of the Republic of Poland:
    1. P.435563 - Circuit for controlling voltages on series-connected capacitors or batteries
    2. P.435562 - Circuit for increasing the input voltage of a four-level NPC inverter powered from a single DC voltage source
    3. P.435564 - Circuit for reducing the variable component in the input DC voltage of a three-level NPC inverter powered from a single energy source
    4. P.435565 - Circuit for converting the energy of two independent DC voltage sources by a four-level NPC inverter