Investigation of the Circuit Tolerances Influence in Multiphase Resonant Converters for Energy Storage Applications

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Abstract: - The following paperwork presents an investigation of multiphase resonant converters for applications in energy storage systems. Models of the examined converters are developed in the software environments of MATLAB and LTspice. Results from simulation examination of the converters during charging of supercapacitors and rechargeable batteries are presented. The influence of the component values variation in one of the modules is investigated. Normalized values of the main circuit currents and voltages are presented. The obtained simulation results are compared to experimental results obtained from a laboratory stand. The presented characteristics provide opportunity for assessment of the converter behavior, as well as, considerations for the design of the modules.

Key-Words: - Circuit Tolerances, Energy Storage, Multiphase Resonant Converters.

1 Introduction

The soft switching operation and the high overall efficiency of the resonant DC/DC converters makes them very useful for implementation in energy storage systems (ESS). Different circuit topologies providing either DC current or DC voltage may be used for charging of energy storage elements (ESE), such as supercapacitors and rechargeable batteries [1, 2].

Due to the specificities of the charging process, an initial charging current limitation may be necessary. Another important issue is the usual necessity of galvanic isolation. Moreover, modular system topologies with several converters operating in parallel to a common load are often used providing higher output power [3-6].

The following paperwork considers a resonant DC/DC converter with three input inverter stages. Due to the circuit features, its operation principle remains unchanged for larger number of modules. Investigation of the circuit component tolerances influence on the converter operation is carried out. Model based design is proposed for simplified examination of the complicated processes observed in the separate stages. Models of the examined modules are developed for optimization of the analysis and the design procedure. The obtained results are used for building of normalized characteristics for the main converter parameters.

2 Single-Stroke Resonant Converter Circuit with Switching Capacitor Voltage Limitation

Fig. 1 presents circuit of a single-stroke resonant inverter with switching capacitor voltage limitation. It is derived from the classical resonant inverter half-bridge topology with reverse diodes. As the name suggests, an operation specificity of the circuit is the voltage limitation across part of the switching capacitor, which results in a limitation of the supply source current during operation at low resistance loads near the short circuit mode. This feature has a significant contribution to the overall circuit performance in ESE charging applications.

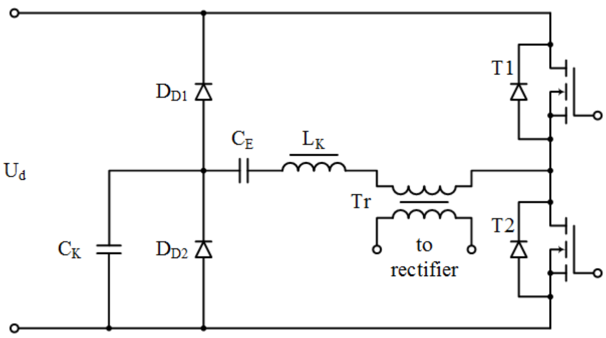

Fig.1. Circuit of a single-stroke resonant inverter with switching capacitor voltage limitation.

Another privilege of this converter is the behavior as an ideal current source with respect to the load, which is very useful for obtaining the constant-current ESE charging mode.

An advantage of the examined inverter circuit compared to similar topologies [7] is the less installed power of the reactive components.

3 Multiphase Converter Topology

In order high output power to be obtained, a multiphase converter topology is proposed. A generalized block-diagram of the particular examined three-phase topology is presented in fig. 2. It consists of three inverter stages with coupling transformers and a three-phase bridge rectifier. The proposed topology allows increase in the input stages number without violation of the converter operation – only a proper phase shift of each inverter control signals should be considered.

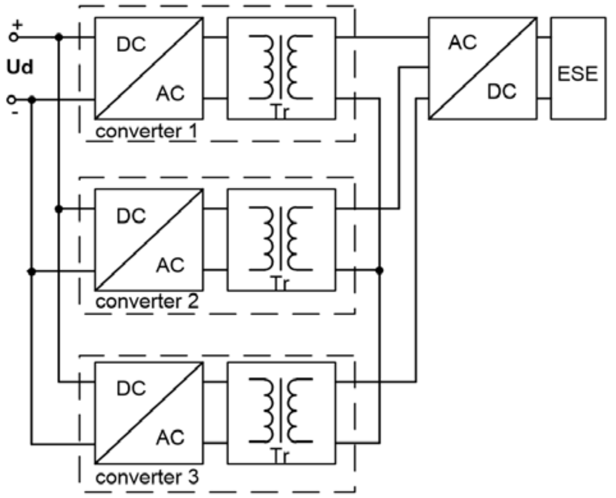

Fig.2. A generalized block-diagram of the proposed multiphase converter.

4 Models of the Proposed Converter

Models of the proposed multiphase converter are developed on a modular principle in the software environments of MATLAB Simulink and LTspice for the purposes of the circuit examination and the design procedures. This modular principle allows comparative analysis of different circuit topologies for realization of one or more converter modules to be carried out without changing the rest of the model. Thus, one and the same generalized converter model can be used for examination of specific topology parts preserving the operating conditions of the overall model.

The full MATLAB Simulink model of the examined multiphase converter is presented in fig. 3. A detailed description of this model and the separate modules in its composition is presented in [8].

Model of the single-stroke resonant inverter with switching capacitor voltage limitation is also developed in MATLAB Simulink in order the circuit to be analyzed during operation as input inverter stage of the proposed multiphase converter. The model is presented in fig. 4.

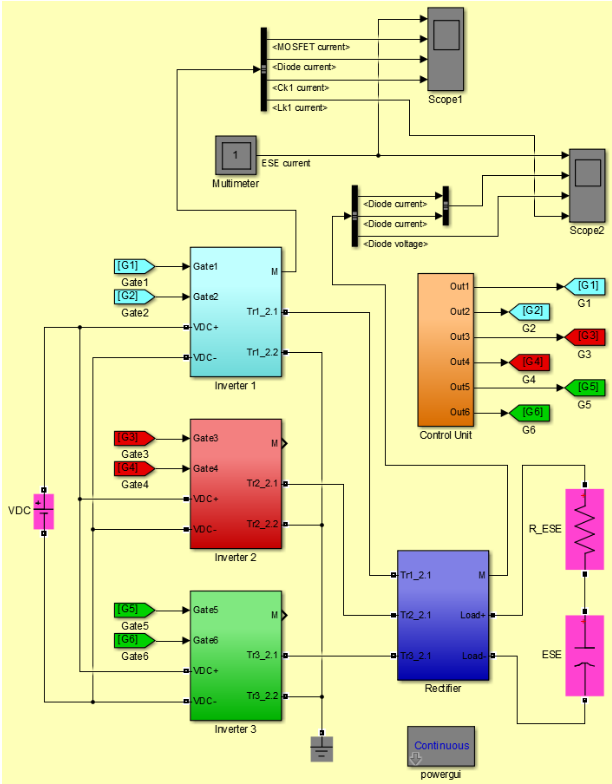

Fig.3. Full MATLAB Simulink model of the converter.

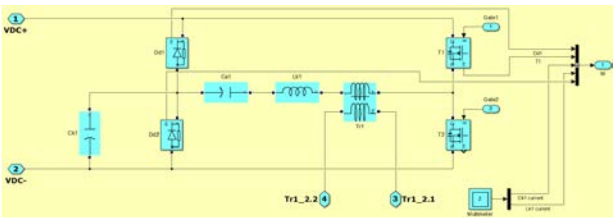

Fig.4. MATLAB Simulink model of the single-stroke resonant inverter circuit.

5 Simulation Results

Results from computer simulations of the proposed multiphase converter are obtained for supply voltage of 30V, and the ESE is represented by a capacitance of 10mF and a resistance of 1Ω (including parasitic resistance of connections). For the purposes of the present investigation, the capacitance representing the ESE is significantly reduced in order to obtain proper illustration of the whole charging process for reasonably small simulation times. The transformer ratio is 1. The other circuit values are as follows:

$$C_K = 2.8\mu F,\ C_E = 0.4\mu F,\ L_K = 135\mu H$$

In order to evaluate the influence of the component tolerances on the circuit operation, a parametric analysis with variation of one of the inverter modules resonant tank inductance LK1 is carried out. The variation is within the ±20% range around the nominal value. In order to preserve the resonant frequency of the stage, correction of the resonant tank capacitors values is also applied. Fig. 5 illustrates the normalized dependence of the two capacitor values from the resonant tank inductance.

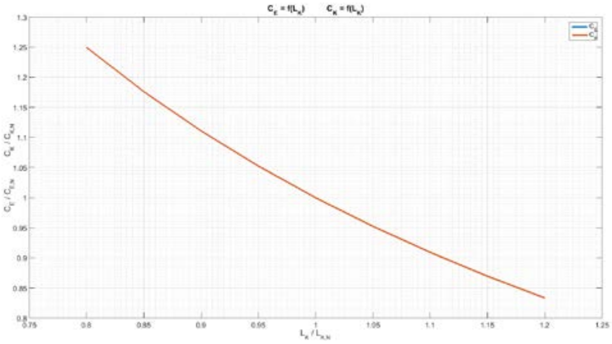

Fig.5. Normalized dependences of CE1 and CK1 as functions of the LK1 value.

5.1 MATLAB Simulation Results

Computer simulations with the developed in MATLAB Simulink model of the proposed converter with single-stroke resonant inverter stages are carried out with respect to the balanced circuit. Waveforms of the main currents and voltages are presented in fig. 6 and fig. 7.

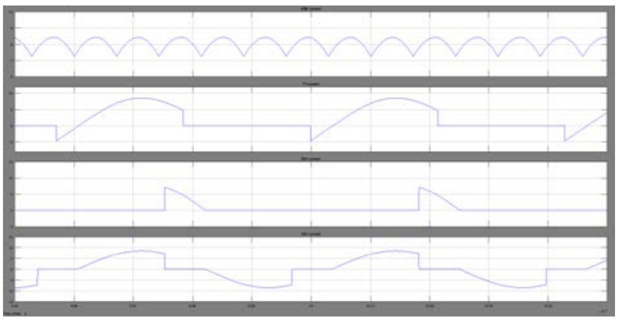

Fig.6. Waveforms of the ESE, the transistor T1, the limitation diode DD1 and the switching capacitor CK1 currents at 10ms simulation time (MATLAB Simulink model).

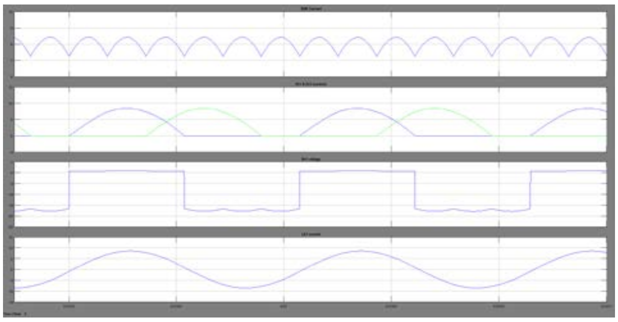

Fig.7. Waveforms of the ESE current, the rectifier diodes DR1 and DR3 currents, the diode DR1 voltage and the resonant inductance LK1 current at 10ms simulation time (MATLAB Simulink model).

A further investigation is carried out in order to determine the influence of the resonant tank component values variation in one of the stages on the overall converter operation. Fig. 8, fig. 9 and fig. 10 present waveforms of the imbalanced circuit main currents and voltages obtained for a 20% increase of the LK1 value. The resonant tank component values of module 1 are as follows:

$$C_{K1} = 2.3755\mu F,\ C_{E1} = 0.3334\mu F,\ L_{K1} = 162\mu H$$

The values in the other converter stages remain intact.

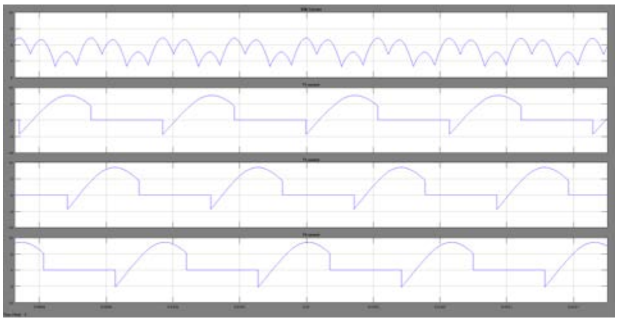

Fig.8. Waveforms of the ESE current and the transistor currents of the three modules (T1, T3 and T5 respectively) at 10ms simulation time (MATLAB Simulink model).

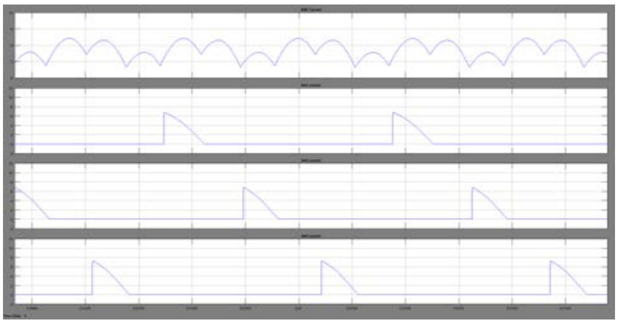

Fig.9. Waveforms of the ESE current and the limitation diode currents of the three modules (Dd1, Dd3 and Dd5 respectively) at 10ms simulation time (MATLAB Simulink model).

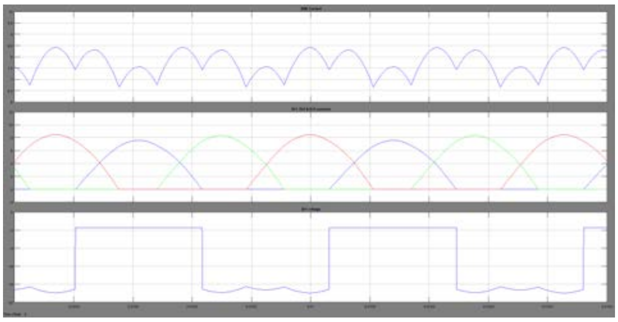

Fig.10. Waveforms of the ESE current, the rectifier diodes Dr1, Dr3 and Dr5 currents and the diode Dr1 voltage at 10ms simulation time (MATLAB Simulink model).

The observed processes are identical for battery charging. From the obtained waveforms, it can be observed that the separate modules operating modes are preserved, and the circuit currents and voltages values are altered. With the change of only one element in the series resonant circuit without resonant frequency (for example, CE is varied without variation of LK) not only current value variations occur but change in the stages operating modes is also possible.

5.2 LTspice Simulation Results

For verification of the obtained simulation results from the model of the proposed multiphase converter in MATLAB Simulink, an identical model is developed in the software environment of LTspice.

The results obtained from the LTspice model of the proposed multiphase converter balanced circuit are presented in fig. 11 and fig. 12. Fig. 13, fig. 14 and fig. 15 present waveforms obtained from simulations of an imbalanced circuit with the above described component values. As it can be observed, the results are identical to those from the MATLAB Simulink model, which verifies both their authenticity.

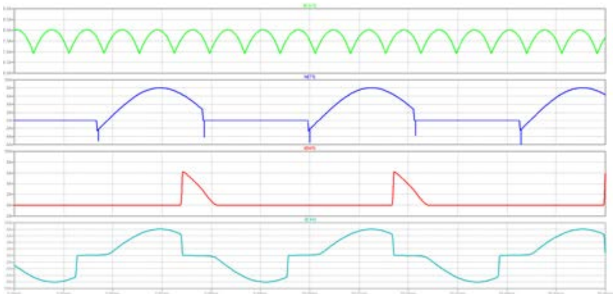

Fig.11. Waveforms of the ESE, the transistor T1, the limitation diode DD1 and the switching capacitor CK1 currents at 10ms simulation time (LTspice model).

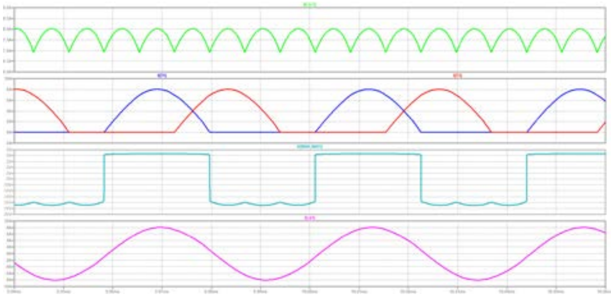

Fig.12. Waveforms of the ESE current, the rectifier diodes DR1 and DR3 currents, the diode DR1 voltage and the resonant inductance LK1 current at 10ms simulation time (LTspice model).

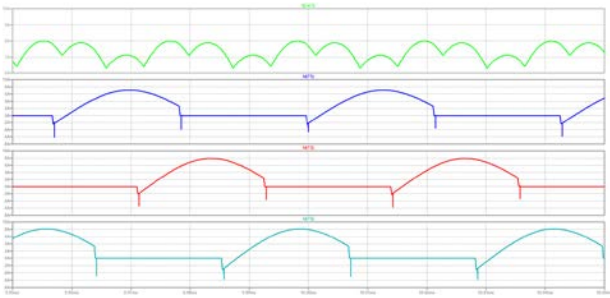

Fig.13. Waveforms of the ESE current and the transistor currents of the three modules (T1, T3 and T5 respectively) at 10ms simulation time (LTspice model).

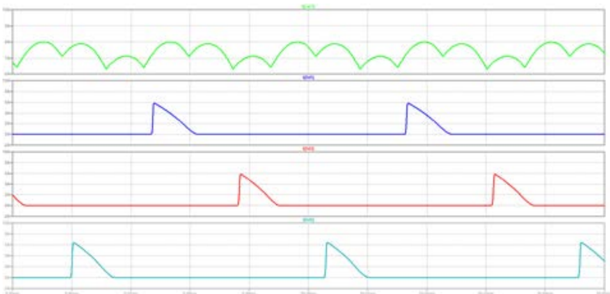

Fig.14. Waveforms of the ESE current and the limitation diode currents of the three modules (Dd1, Dd3 and Dd5 respectively) at 10ms simulation time (LTspice model).

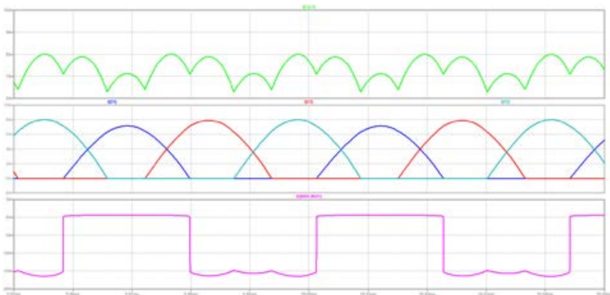

Fig.15. Waveforms of the ESE current, the rectifier diodes Dr1, Dr3 and Dr5 currents and the diode Dr1 voltage at 10ms simulation time (LTspice model).

5.3 Influence of the Circuit Elements Tolerances

The tolerances of the elements in the examined circuit play an important role in the whole converter performance. As it can be observed from the simulation results, deviation in one of the modules resonant tank values results in imbalance between the separate stage currents.

Fig. 16 to fig. 20 present variations of the basic currents of the converter stages. These currents are taken into consideration when choosing the circuit elements.

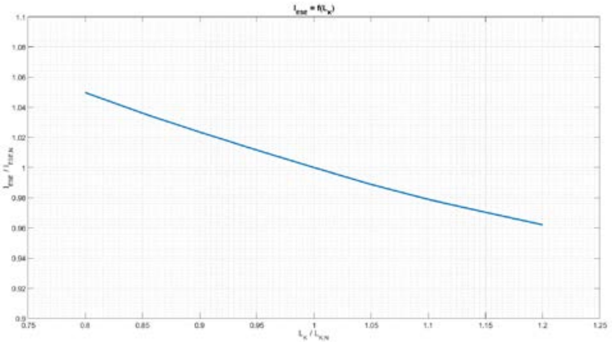

Fig.16. Normalized characteristics of the average ESE current as function of the LK1 value.

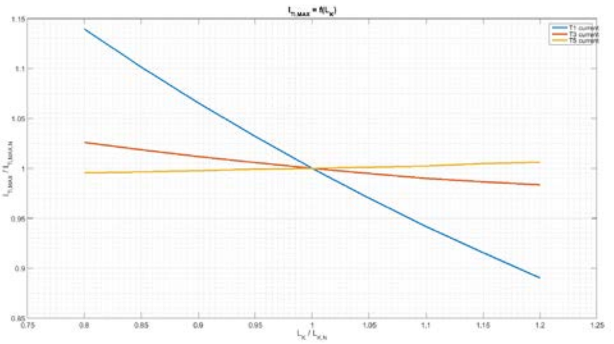

Fig.17. Normalized characteristics of the maximum transistor currents of the three modules as functions of the LK1 value.

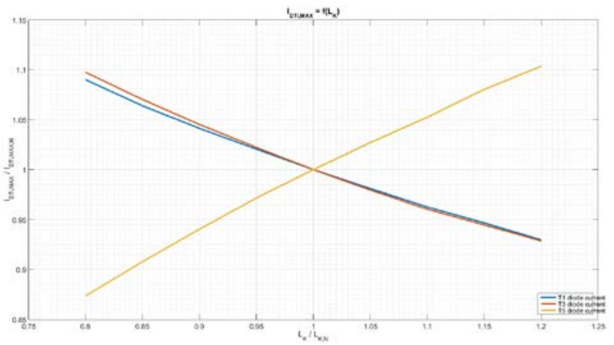

Fig.18. Normalized characteristics of the maximum reverse diode currents of the three modules as functions of the LK1 value.

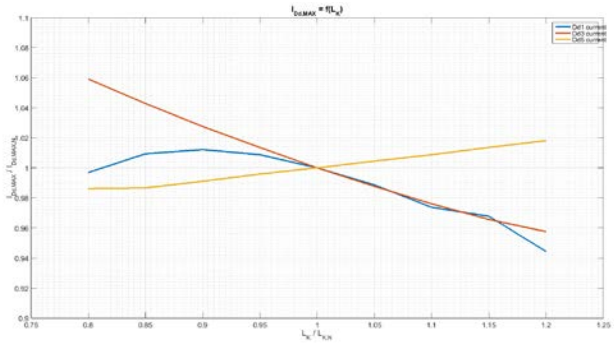

Fig.19. Normalized characteristics of the maximum limitation diode currents of the three modules as functions of the LK1 value.

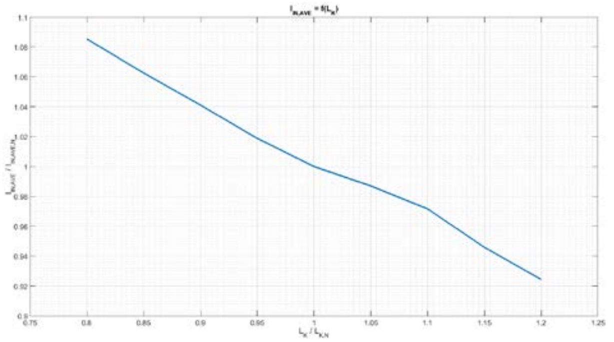

Fig.20. Normalized characteristics of the average input supply current as function of the LK1 value.

From the presented characteristics, it can be observed that a 20% reserve to the nominal values is sufficient to satisfy the asymmetry of the modules. In order to compensate for the values of the capacitors and to preserve the resonant frequency, a proper choice of inductance with suitable value is necessary.

6 Experimental Examinations

For further verification of the obtained simulation results, experimental examinations of the proposed multiphase converter based on single-stroke resonant inverter input modules are carried out on a laboratory stand. The presented waveforms (fig. 15 to fig. 18) correspond to the charging process of a 58F/16V supercapacitor. The other circuit parameter values are identical to the ones from the two simulation models.

The experimentally obtained current waveforms present the operation of an imbalanced converter due to the tolerances of the circuit elements. As a result of these tolerances, an imbalance between the separate inverter stage currents occurs. This can easily be observed from the non-symmetric ESE current waveform, as well as, from the rectifier diode current waveforms having different maximum values.

The presented in fig. 21 and fig. 22 waveforms of the diodes and transistor currents are obtained via a current probe with ratio of 10mA/mV. The waveform of the ESE current is obtained via a measurement shunt.

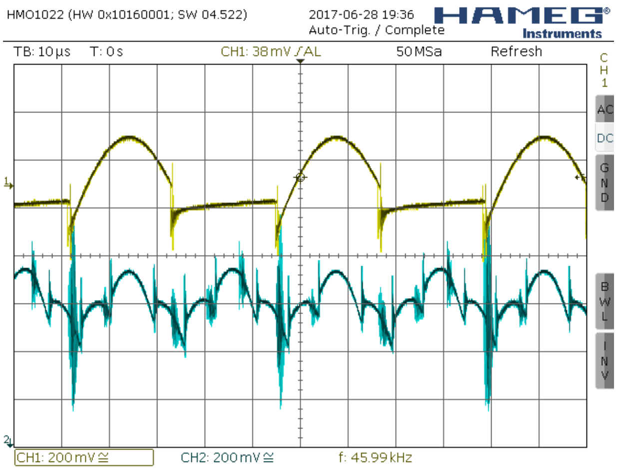

Fig. 21. Waveforms of the transistor T1 and the ESE currents.

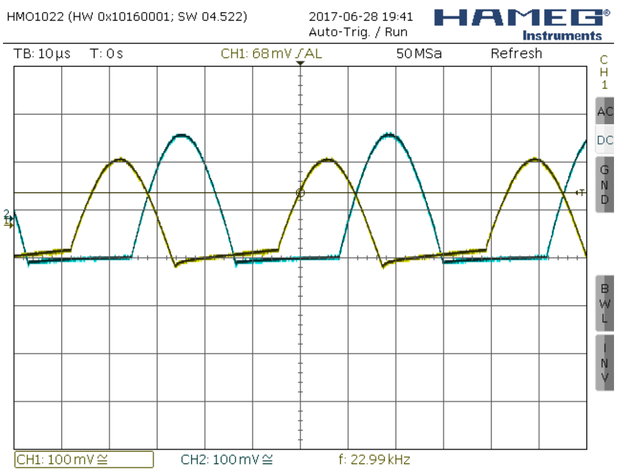

Fig. 22. Waveforms of the diodes DR1 and DR3 currents.

7 Conclusion

An investigation of a multiphase converter for charging of ESE is carried out.

Models of a multiphase converter for charging of ESE are developed in the software environments of MATLAB Simulink and LTspice. The developed MATLAB model is based on a modular principle allowing examination of converters with different number of phases.

The investigations are carried out with variation of the LK value of one of the modules followed by a corresponding correction of the CE and CK values in order to preserve the resonant frequency of the series resonant tank. Normalized dependencies for the main currents and voltages of the separate multiphase converter modules are built. From these characteristics, the influence of the parameter variations in one of the modules on the operation of the others can be determined.

With variation of the resonant tank element values, a stage operating mode is changed with respect to those of the other modules. Moreover, this change causes different changes in the operating modes of the other two stages although they have identical component values.

The developed models allow parametric analysis to be carried out. Because of the complexity of the circuit processes and the lack of steady state operation during ESE charging, analytical expressions for the circuit currents and voltages are difficult to be obtained. For design of such converters model based design is used.

Another specialty is the rectifier operation with two diodes from the same group (anode or cathode) operating simultaneously during part of the time as the stage operates in current rectification mode. This can be observed from the waveforms presented in fig. 9, 14, and 21.

Obtaining different operating modes of the multiphase converter allows to evaluate in which cases a synchronous rectifier realization is possible in order to increase the converter efficiency.

The carried out examinations show that the variation of the separate modules currents and voltages is within the ±20% range compared to these values for identical parameters of all of the stages. Depending on the magnitude of the desired frequency detuning for identical modules and with variation of the resonant tank component values, it is possible different operating modes to occur, such as two of the modules operating above the resonant frequency with the third operating below.

The carried out research is realized in the frames of project BG05M2OP001-2.009-0033, Operational Program Science and Education for Smart Growth 2014-2020.

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