Power converter circuits for recuperation of the regenerative braking energy in rail vehicles

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Abstract **- Electric rail transport offers a sustainable development in the transport sector with regard to an increasing urbanization and adverse climate changes. Due to rising energy costs, there is also a need for adequate energy saving solutions in this type of transport. In order to save energy and increase performance of the vehicle the recuperation of regenerative braking energy solution is used. The stored energy could be used to increase performance and energy efficiency during acceleration and even enable autonomous drive. This paper considers storing of regenerative braking energy of rail electric vehicles in lithium-ion batteries and supercapacitors, installed on the vehicle. Discussed power converters' topologies perform energy conditioning and optimal energy management between vehicle's storage, power train and power line, during traction, braking and driving with constant speed. Simulation models of typical power converters which are used for this purpose have been developed and simulation experiments were conducted. The comparative analysis of simulation results highlights the advantages and disadvantages of the simulated converters and the observed types of energy storage with respect to the set criteria.**

Key words – regenerative braking; topologies; railway vehicles; energy storage elements; DC/DC converters

I. INTRODUCTION

Electric railway vehicles are a safe, economic and ecologically viable choice for transporting goods and people. To further reduce greenhouse gas emissions and enhance the energy efficiency, necessary improvements must be undertaken. Storing and reusing the energy obtained during dynamic braking is one of the most effective methods to increase energy efficiency in electric railway vehicles.

Dynamic braking energy is the transformation of the vehicle's kinetic energy into electrical energy during deceleration and it is based on the ability of the electric motors to operate in generating mode. Uncontrolled energy returns to the power supply grid can cause over-voltages and decrease the grid's quality if there are no demands for that energy. Systems that can improve the power supply quality and which also enable the storage and subsequent use of dynamic braking energy are called regenerative braking systems. In these systems, the braking energy is mainly stored in battery and/or supercapacitor modules and can be used for starting and accelerating the vehicle, as well as for limited autonomous driving without a power supply.

There are two approaches in developing and implementing a regenerative braking system for railway vehicles. One approach consists of installing an energy storage system (ESS) outside the vehicle as wayside or stationary ESS, which enables the capture of surplus energy in the power supply grid during braking and returning the stored energy during acceleration. Stationary energy storage units improve the grid's stability. The second approach is based on integrating the ESS in the vehicle itself. This mobile regenerative braking system can provide a limited autonomous drive without catenary.

Energy storage elements are connected to the main drive's DC link through a bidirectional DC/DC converter which has the task of controlling the flow of braking energy according to demands of the vehicle and energy storage element. The goal of this paper is to give a review of typical and most utilized bidirectional DC/DC converter topologies used in mobile regenerative braking systems of railway vehicles.

II. DC/DC CONVERTER REQUIREMENTS IN REGENERATIVE BRAKING SYSTEMS

Energy flow in regenerative braking systems is between the main drive inverter's DC link and the energy storage element. Since the DC link's voltage level is usually different from the voltage of energy storage element, a bidirectional DC/DC converter is necessary to adjust voltage levels and control energy flow according to the requirements set by the vehicle and energy storage element.

Generally, in order to simplify converter controllability, the energy storage element's voltage level is lower than the DC link's voltage level. This means that during braking the DC/DC converter will charge the energy storage element and will function as a buck (step-down) converter; and during the vehicle's acceleration it will discharge the energy storage element and function as a boost (step-up) converter.

It is necessary to consider several parameters when choosing a DC/DC converter topology.

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The converter efficiency is always an important parameter and the goal of development is to achieve highest efficiency possible, especially in systems with larger power. Also, the DC/DC converters in these systems should operate reliably in a wide temperature range and in terms of significant cyclic loads.

The transfer voltage ratio of the DC/DC converter is an important parameter, especially if the converter is connecting an energy storage element with a much lower voltage level than the power supply grid's voltage. If output and input ratio is over 20, it is recommended using topologies with a galvanic isolation i.e. a transformer [1]. A suitable turns ratio achieves the desired voltage increase. Converters using a transformer are also safer to use, since in a case of malfunction the energy storage element and rest of the system are electrically separated.

Another important parameter in selecting the topology of a DC/DC converter is the number of power semiconductor switches used. Increasing the number of semiconductor switches increases the number driving circuits and the complexity of the converter control unit. The converter's mass and dimensions also increase, as well as its price. On the other hand, a higher number of semiconductor devices lowers the voltage and current stresses and possibly losses. Considering the above, a compromise must be made between lowering the complexity and price in contrast to lowering the total power losses.

Energy storage elements used in regenerative braking systems are most commonly lithium-ion batteries and/or supercapacitors. These storage elements require a constant charge or discharge current with minimal ripple. Therefore, converters in these systems must have the lowest possible current ripple on the energy storage element side.

III. DC/DC Converters Topologies In Regenerative Braking Systems

A. Half-bridge buck-boost DC/DC converter

The half-bridge buck-boost DC/DC converter is the simplest and most utilized bidirectional DC/DC converter topology, shown in Fig. 1.

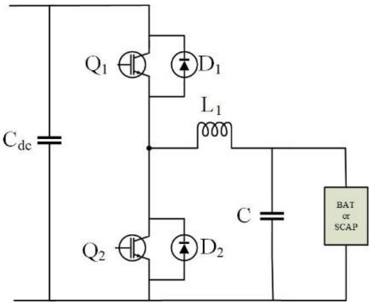

Figure 1. Half-bridge buck-boost DC/DC converter

The capacitor C_{dc} represents the main drive's DC link and the block BAT/SCAP represents the energy storage element. During braking, energy flows from the DC link towards the energy storage element i.e. the converter functions as a buck converter. The duty cycle of transistor Q_1 controls the amount of power conveyed to the battery. During this mode of operation, the inductor L_1 functions as a filter. When the energy flows from the battery towards the DC link, the converter functions as a DC/DC boost converter. The duty cycle of transistor Q_2 controls the amount power sent to the DC link. During either flow direction, the converter operates in continuous-current mode.

This topology advantage is that it only uses two controlled switches in complementary duty cycles which simplifies the excitation circuitry and control. A small number of switches and the fact that this topology does not use a transformer, its efficiency does not fall below 90% [2].

This topology disadvantages are the limited voltage level increase during boost mode operation and that it does not have galvanic isolation of the energy storage element [3].

B. Interleaved buck-boost DC/DC converter

The interleaved buck-boost DC/DC converter is a parallel connection of two or more half-bridge DC/DC converters. The control signals are phase shifted by an angle of 360°/n, where n is the number of parallel phases. Fig. 2 shows an example of the converter with 3 parallel phases.

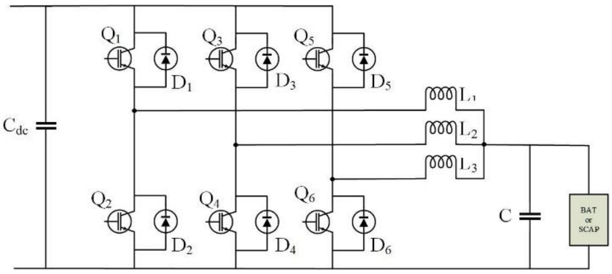

Figure 2. Interleaved buck-boost DC/DC converter

The advantage of this converter is a lower charging current ripple since phase-shifted signals control each phase. For this reason, filters of lower values and dimensions are used. Also, due to current split on multiple phases (I/n), for the same switching frequencies and for the same average output current value, the total losses of the semiconductor switches in this topology are smaller in relation to single phase half-bridge buck-boost DC/DC converter shown in figure 1. For this reason, this converter topology results in higher efficiency and power density [4], [5].

The main disadvantage is the higher cost due to the higher number of semiconductor devices integrated in the converter as well as a more complicated control algorithm [4].

C. Buck-boost DC/DC converter with coupled inductors

Fig. 3 shows a buck-boost DC/DC converter with magnetically coupled inductors with the same number of turns [5].

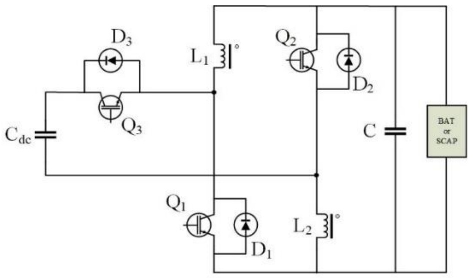

Figure 3. Buck-boost DC/DC converter with coupled inductors

In boost mode, when energy flow is from the BAT/SCAP energy storage element to the DC link C_{dc}, Q_3 switch is not conducting and a control signals are sent to switches Q_1 and Q_2 simultaneously. When Q_1 and Q_2 are conducting, inductors L_1 and L_2 are in parallel and are accumulating energy from the BAT/SCAP energy storage element. When Q_1 and Q_2 are switched off, the inductors are in series with the load and delivering energy through the diode D_3.

In buck mode, when the energy flow is reversed, a control signal is sent to Q_3 while Q_1 and Q_2 are off. When Q_3 is conducting, the inductors are in series and act as a filters along with the capacitor C. When Q_3 is switched off, current flows through forward-biased diodes D_1 and D_2.

Advantages of using this topology instead of the half-bridge buck-boost DC/DC converter are a lower current stress of the switches, a higher efficiency and a higher voltage increase during boost mode [5].

D. Dual active full-bridge DC/DC converter

This DC/DC converter consists of two bridge converters, one on the high voltage side (primary) and one on the low voltage side (secondary) of a high-frequency transformer T_r, Fig. 4. Using transformer, galvanic isolation and a necessary voltage increase or decrease are achieved. Using the leakage inductance L_k and by implementing commutation capacitors C_{c1}–C_{c8}, soft-switching is accomplished to reduce switching losses [7].

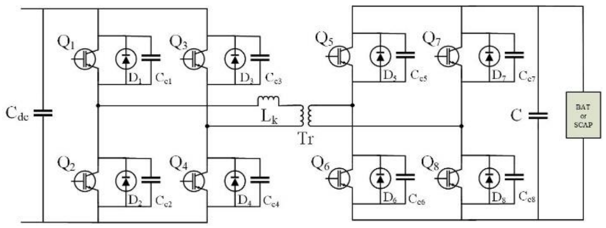

Figure 4. Dual active full-bridge DC/DC converter

Depending on energy flow direction, one converter functions as an inverter and the other as a full-wave rectifier. E.g. if energy flows from the DC link to the battery, the converter connected to the DC link functions as an inverter and the converter connected to the battery functions as a rectifier. The swicthes are switching in diagonal pairs with a duty cycle of 0.5, generating a square-wave voltage waveform on the primary and secondary. Multiple power flow control methods exist for this converter topology. A basic and commonly used one is controlling the phase shift between the transformer's primary and secondary, called the *phase shift control strategy*.

The advantage of this topology is the operation on high frequencies and the consequently usage of a relatively small transformer to achieve galvanic isolation and high power density assuming that the leakage inductance is sufficiently low [3]. Efficiency in this converter is around 95%, both for low and high power applications [8], [9], [10].

The disadvantage of this converter is a high input and output current ripple, which can be reduced by adding an adequate filter [3]. A high number of semiconductor devices and a complex control algorithm can represent a challenge during design and implementation of this topology.

E. Dual active half-bridge DC/DC converter

This converter consists of two half-bridge converters, one on the high voltage side (primary) and one on low voltage side (secondary) of a high frequency transformer T_r.

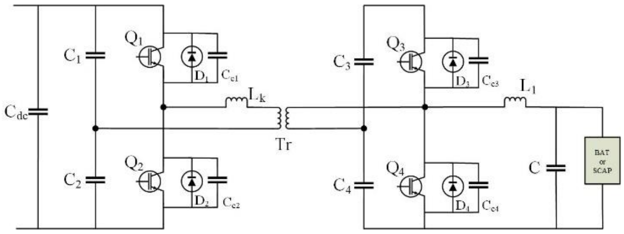

Figure 5. Dual active half-bridge DC/DC converter

Similarly as in the dual active full-bridge DC/DC converter, the amount of power and direction of energy flow is controlled through the primary and secondary voltage phase shift. During power transfer from the high voltage side to the low voltage side, switches Q_3 and Q_4 along with the inductor L_1 achieve a DC/DC buck converter. During power transfer from the low voltage side to the high voltage side, the aforementioned components accomplish the effect of a DC/DC boost converter. The voltage on the primary and secondary is a square-wave waveform. Primary voltage amplitude is equal to half of the DC link voltage. Secondary voltage amplitude is equal to half the voltage on the series capacitors C_3 and C_4.

In comparison with the dual active full-bridge DC/DC converter, the dual active half-bridge DC/DC converter has half the amount of semiconductor devices for the same amount of rated power. Furthermore, the buck/boost converter on the low voltage side achieves lower current ripple on the side of the energy storage element and lower switch current stresses [10]. Soft-switching is achieved equally on every switch for both energy flow directions [10].

One of the main disadvantages of this topology is that peak load current flows through the capacitors in the capacitive voltage divider [3], [10].

IV. SIMULATION OF FUNCTIONAL BEHAVIOR OF DC/DC CONVERTER IN REGENERATIVE BRAKING SYSTEM

In this chapter, a simulation model of the DC/DC converter is developed. This simulation model is used to control the flow of braking energy of the rail vehicle during charging and discharging of the supercapacitor module. The simulated topology is dual active full bridge DC/DC converter. This topology was chosen with the intent to assess the current ripple level of the energy storage element. The simulation model was developed using PLECS simulation software, and after simulations were carried out, results are commented.

The simulation model consists of DC link capacitor connected to a grid modeled as an ideal voltage source of 600V with a serial connected resistor modeling the internal resistance of the grid. The electric motor and inverter are modeled as an controllable current source. The controllable current source models the acceleration and braking of the vehicle. The supercapacitor is modeled as a block from the PLECS model base and its parameters can be modified accordingly. The parameters for supercapacitor model used in this simulation were taken from Maxwell BM0D0063 P125 B08 supercapacitor module datasheet and are listed in Table 1. In simulation four such models connected in series were used.

Table 1. Supercapacitor module Maxwell BM0D0063 P125 B08 parameters

Rated capacitance	**Maximum ESR**	**Rated Voltage**	**Leakage Current**
63 F	18 mΩ	125 V	10 mA

Figure 6 shows the scheme of a simulation model of a dual active full bridge DC/DC converter. The simulation model parameters are presented in Table 2, and the simulation parameters are presented in Table 3.

Table 2. Simulation model parameters

Component	**Parameter**	**Value**
Q1 - Q8, Q_brake	Ideal IGBT with ideal diode	
	Switching frequency (Q1-Q8)	20kHz
Cdc	Capacitance	30e-3 F
	Initial Voltage	600V
	ESR	0.009 Ω
Lk	Leakage Inductance	5 µH
	Initial current	0 A
Tr – ideal transformer	N1/N2 (transfer ratio)	1.2
Rprimary	Resistance of primary coil	0.001 Ω
Rsecondary	Resistance of secondary coil	0.001 Ω
C	Supercapacitor capacitance	30 F
	Initial Voltage	480 V
V_dc – grid voltage	Voltage	600 V
Rvdc – grid resistance	Resistance	0.00387 Ω
R_brake	Resistance	1 Ω

Table 3. Simulation parameters

Parameter	**Value**
Max step size	1e-6 s
Relative tolerance	1e-3
Initial step size	Auto
Absolute tolerance	Auto
Refine factor	1
Solver type	Variable-step
Solver	RADAU (stiff)

In this simulation, the control of the converter is performed by achieving a phase shift between the primary and secondary transformer voltages. In the case of discharging of the supercapacitor, the secondary voltage precedes the primary voltage, and in the case of charging, primary voltage precedes the secondary voltage.

In real applications, it is necessary to implement the control of phase shift in order to control charging and discharging power, but since the goal of this chapter is to describe only the functional behavior of the converter in the regenerative braking system, the converter is controlled in such a way that the phase shifts are constant.

The modeled converter is controlled via the "CONTROL UNIT" block. From figure 6 it can be seen that inputs to the block „CONTROL UNIT“ are: DC link voltage, supercapacitor voltage and current from current source which in this simulation models the current on the input of the inverter of electric drive. Based on these variables, the control signals for the converter switches Q1-Q8 and the brake resistor switch Q_brake are determined. The control system is implemented in such a way that the control block "CONTROL UNIT" based on the direction and the amount of current of current source and of the voltage of the supercapacitor, starts or stops charging and discharging of the supercapacitor module.

The simulation was performed with the profile of the current source shown in the top graph of figure 7 for the case when initial voltage of supercapacitor is 400V which represents 80% charge level. Negative current source profile represents acceleration of the vehicle while positive current profile represents dynamic braking of the vehicle.

The negative direction of the current source current in this simulation means that the direction of the current is from the DC link to the inverter of electromotor drive. When the direction of this current is negative, and when its absolute value is greater of the set threshold value, and if supercapacitor voltage is greater than 250V converter starts discharging supercapacitor by generating phase lead of secondary voltage relative to primary voltage. When direction of current is positive and greater than the set threshold value, and if supercapacitor voltage is less than 500V, the converter starts charging of the supercapacitor by generating phase lead of primary voltage relative to secondary voltage.

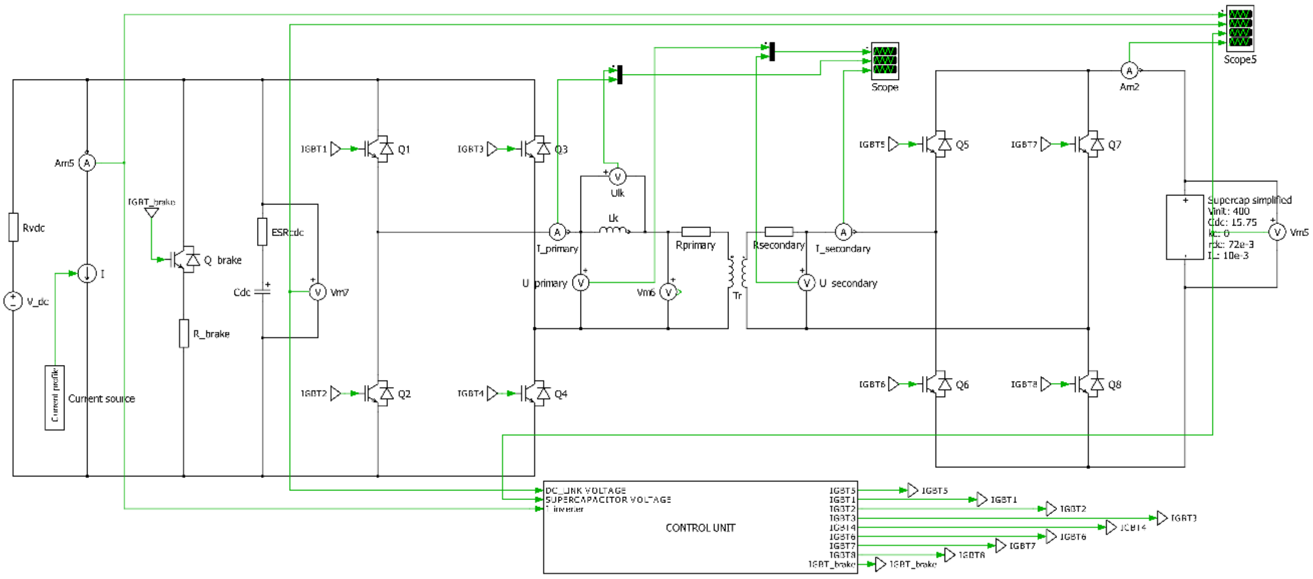

Figure 6. Simulation model of dual active full bridge converter

Braking assembly made of switch Q-brake and resistor R_brake serves to stabilize the DC link voltage during dynamic braking. In case the DC link voltage rises above 610V, the Q_brake switch closes and the excess dynamic braking energy is dissipated through braking resistor as heat while the DC link voltage does not falls below 605V.

The current source profile, DC link voltage, supercapacitor voltage and current during discharge and charge process are shown in Figure 7.

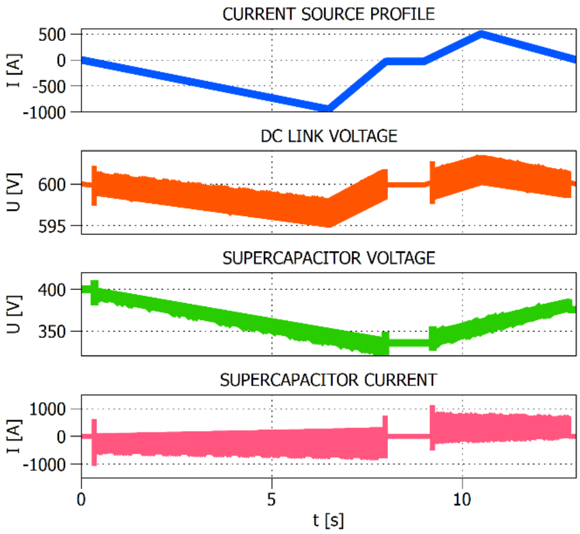

Figure 7. The current source profile, DC link voltage, supercapacitor voltage and current during discharge and charge process

Figure 8 and Figure 9 show two periods of the above mentioned values during discharging and charging. It is possible to notice substantial ripple current of charging and discharging of supercapacitor. It is already mentioned in chapter 3.4 that the biggest drawback of this topology is significant current ripple on the side of energy storage element.

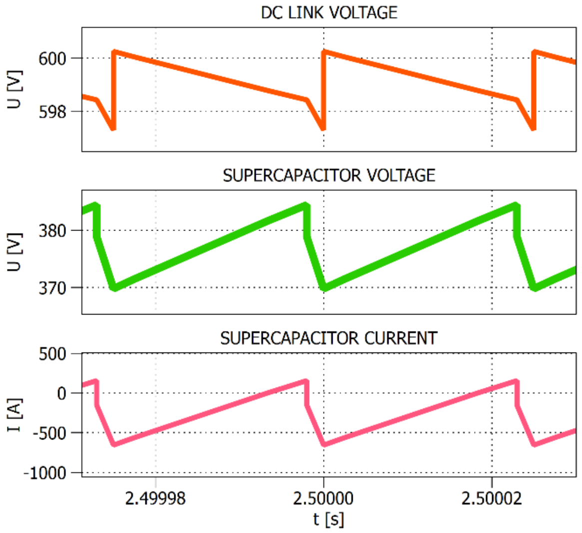

Figure 8. Waveforms of DC link voltage and supercapacitor voltage and current during discharging

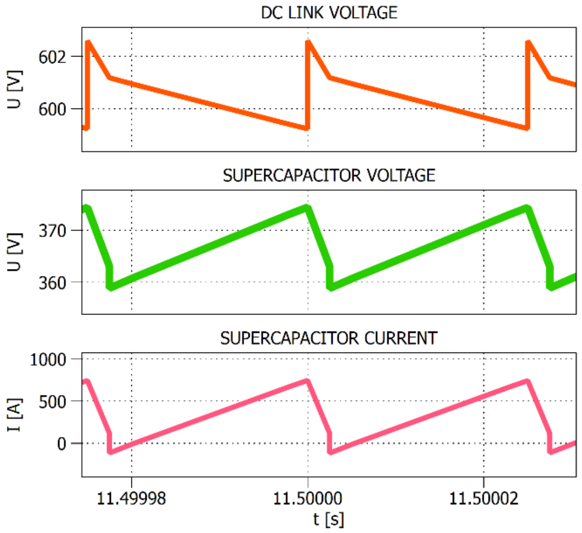

Figure 9. Waveforms of DC link voltage and supercapacitor voltage and current during charging

Figure 10 and Figure 11 show the phase shifts of primary and secondary voltages of transformer and corresponding currents. In addition to primary current, the voltage of leakage inductance is shown (green color).

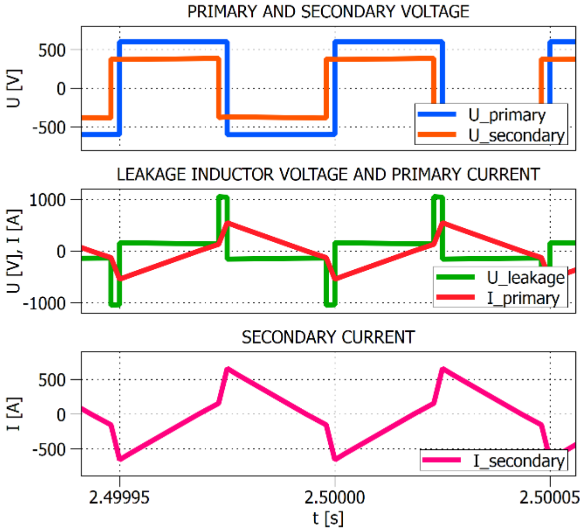

Figure 10. Waveforms of voltages and currents in the transformer during discharging

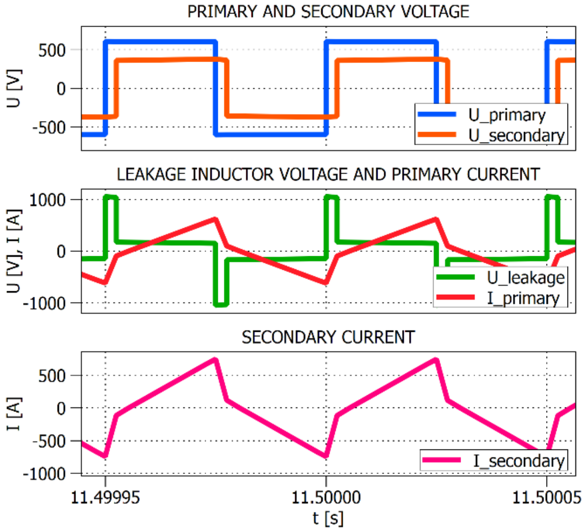

Figure 11. Waveforms of voltages and currents in the transformer during charging

V. CONCLUSION

The role and significance of regenerative braking systems is described and the main requirements for DC/DC converters in regenerative braking systems are presented. There is a wide variety of topologies that can be used in regenerative braking systems, and the ultimate choice depends on the power, the ratio of output and input voltage, as well as price and complexity. An overview of some of the basic topologies of DC/DC converters used in regenerative braking systems has been presented. The basic work principles and the most significant advantages and disadvantages of each adduced topologies are presented as well. The simulation of the regenerative braking system with dual active full bridge DC/DC converter was performed and the results obtained were matched with the theoretical predictions.

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