Bi-Directional High-Voltage DC-DC-Converter for Advanced Railway Locomotives

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***Abstract* -- Increase of power demands of DC electric locomotives requires increasing catenaries voltage (which presently is 3 kV, 1.5 kV and 0.75 kV, respectively) 4, 6, 8, 10 times and more. At the traction substation, the rectifier will be adapted. The existing traction contact network (catenaries) is kept for direct current, and the novel N-cell dc/dc bidirectional converter without transformer will be located on the electric locomotive. Each cell voltage is defined by the locomotive power train DC input level, thus balancing of capacitor voltages is not required. Simulation results of the proposed 6-cell converter have confirmed the validity of predicted properties of the converter. Realization of a 10 kW model unit has been already started. The proposed converter added with four alternating current valves and the reversible rectifier, allows implementing of the galvanic separation of the load by using the output transformer operating at raised frequency.**

***Index Terms*--High-voltage cell-topology dc-dc converter, high-voltage traction grid, railway locomotives, recuperation capability.**

INTRODUCTION

Today, two basically different systems of electrification of railways co-exist in the world. We find direct voltage systems (mainly 3 kV (DC) and 1.5 kV (DC)) and single-phase alternate voltage systems (mainly 25 kV at 50 Hz or 60 Hz and 15 kV at 16 2/3 Hz). Electric locomotives for DC supply systems exhibit a simpler electric equipment using DC traction machines as well as three-phase AC traction machines (more often induction machines than synchronous machines). Such system do not have the AC feeding system problems through asymmetrical loading of the feeding three-phase power supply system and inductive voltage drop at catenary but have obvious restrictions on power because of a low voltage at the catenaries. In the sixties of the last century, tests of thyristor-capacitor systems of electrification were carried out in Russia [1] and in the seventies in Italy [2] with 6 kV DC. However, these experiences have not led to a new concept for DC electric locomotives due to the unavailability of powerful transistors and GTO-thyristors at that time.

Consequently, the most powerful electric locomotives have been designed for single-phase AC electric supply systems with rated voltages of 25 kV and 15 kV (rms). A further increase in power is limited widely by growth of volume and weight of the single-phase transformer on such an electric locomotive and weight and volume of the standard AC unity power factor input converter.

The availability of powerful high-voltage IGBT-transistors made it feasible to build an electric equipment of an AC electric locomotive without the low-frequency heavy transformer (50 or 16 2/3 Hz), having replaced it on transformers of medium frequency (400 Hz) [3] or (relatively) high frequency (18 kHz) [4]. Now the increase in power of a future electric locomotive is not limited to weight and dimensions of the transformer.

New technical designs for transformerless step-up / step-down dc-dc converters (also capable of handling opposite direction power flow for regenerative Braking, recuperation) allow an increase of power of electric locomotives using direct current supply by increasing the voltage in the contact network to a high extent above 3 kV. This paper proposes a favorable solution for the problem described.

The need for electric locomotives with very high power ratings comes along with increase of freight traffic with railway transportation and increase in train speed. The operating stock of locomotives, passenger and freight wagons is displayed in Table I according to International Rail Statistics [5], [6].

TABLE I
OPERATING STOCK OF LOCOMOTIVES, CARRIAGES AND FREIGHT CARS AT VARIOUS COUNTRIES

Country	Quantity of locomotives, thousand pieces	Quantity of carriages, thousand pieces	Quantity of freight cars, thousand pieces	Quantity of locomotives per 1000 km track
USA	19.7	(no data available)	500.0	2.1
China	14.9	37.2	450.0	1.6
Russia	12.0	41.5	540.5	2
India	7.6	8.9	222.1	0.7

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Given through an average service life of an electric locomotive with 25 - 30 years and a number of electric locomotives operating worldwide at more than one hundred thousand units, annual updating of locomotives should reach 3,5 - 4 thousand units worldwide. According to Rail International the leading companies on release of locomotives are Bombardier (25%), Alstom (19%), Siemens (14%), General Electric (9%), Ansaldo Breda (6%).

With reference to Russia it means that at least 100 to 200 powerful locomotives for cargo trains should be put into service per year. The strategy of development of a railway transportation in the Russian Federation up to year 2030 [7] emphasizes that Russia wins first place in the world on extent of the electrified railways by managing more than 20 % of turnover of goods of all railways of the world. Obviously, an increase of catenaries voltage for DC up to a level 12-18 kV is forecasted by general necessity of higher levels of DC voltage [8]. Today, the traction catenaries network of railways in Russia runs on 3 kV (DC) but exhibits isolation for 20 kV (DC). That allows easily to perform a voltage increase at the catenaries to 12 kV (DC).

NOVEL DC POWER TRAIN CONCEPT BASIC DATA AND BOUNDARIES

The necessary increase in catenaries voltage raises the task for development of new designs and types of rolling stock (locomotives) and elements of a suitable high-power supply infrastructure. We propose a special concept for designing the electric equipment for future electric locomotives at DC traction network operating at 12-18 kV or even above [9]-[11].

A new high-voltage bidirectional network at direct voltage level of 12 - 18 kV is combined with the existing power train system of electric locomotives at 3 kV level equipped with direct current traction engines (electric locomotives of type EP1, EP2k), and with asynchronous traction engines (electric locomotives of type EN3, EP10, look at Fig. 1).

Fig. 1. Electric double-system (AC and DC) locomotive EP10

The same converter with IGBT-transistors with twice smaller voltage can be used for electric locomotives operating at a constant voltage of 1.5 kV. In the scheme considered with four capacitor-transistor cells and with IGBT-transistors of 3.3 kV, a contact network of 6 kV will be connected to an existing drive equipment of an electric locomotive on 1.5 kV. In addition, a converter composed of two, four, six, etc. cells can work at a contact network voltage level of 9 kV, 12 kV, 15 kV, etc.

CIRCUIT SCHEMATIC AND OPERATION PRINCIPLE OF PROPOSED DC-DC CONVERTER

For dc-dc step-down operation using turn-off devices like GTO thyristors or IGBTs, the converter can be designed based on single-phase multilevel inverters with neutral-point clamping diodes (NPC) or with cells using floating capacitors (FCC). However, the voltages at the extreme clamping diodes and extreme floating capacitors are equal or comparable with the pretty high converter input voltage. In our case this amount of voltage will be 6 times the target voltage (at a 6-cell dc-dc converter), or even 8 or 10 times higher for excessively high catenaries voltage. That means a corresponding constructive increase of peak voltage stress on certain elements of the converter.

The proposed new dc-dc converter overcomes this basic problem. The voltage at any element of the converter practically does not exceed the output voltage of the converter at any number of the factor of voltage transformation. It is based on the concept of the “Marx Converter” by operating all capacitors of the converter at series connection when switched to the voltage of catenaries network u_{high} and their subsequent parallel connection at their discharge state supplying the load at u_{low}. Control of the duty cycle of charge / discharge allows adjusting the average value of output voltage of this dc-dc converter.

With reference to the electric drive power train of electric locomotive EP2k all existing relay-rheostat systems providing discrete voltage steps to traction engines are eliminated. Now a smooth regulation of the direct voltage at the traction engines is realized by means of PWM. The converter integrates a switched capacitor voltage divider unit and a dc-dc-step-down chopper. The scheme of the proposed simplified basic six-stage converter circuit is displayed in Fig. 2.

By their consecutive inclusion through control of corresponding IGBT-transistors (6.5 kV voltage rating) these six capacitors Cp3-Cp2-Cp1-C1p-C2p-C3p are charged by u_{high} at total contact network voltage rating equal 18 kV up to a voltage of 3 kV for every capacitor. The inductive load current at u_{low} becomes separated from charging circuit through inverse diodes of transistors Sl1, Sp1, Sh1 and S1l, S1p, S1h, respectively, carrying out the function of freewheeling diodes. The PWM zero interval of the load voltage is formed through this path.

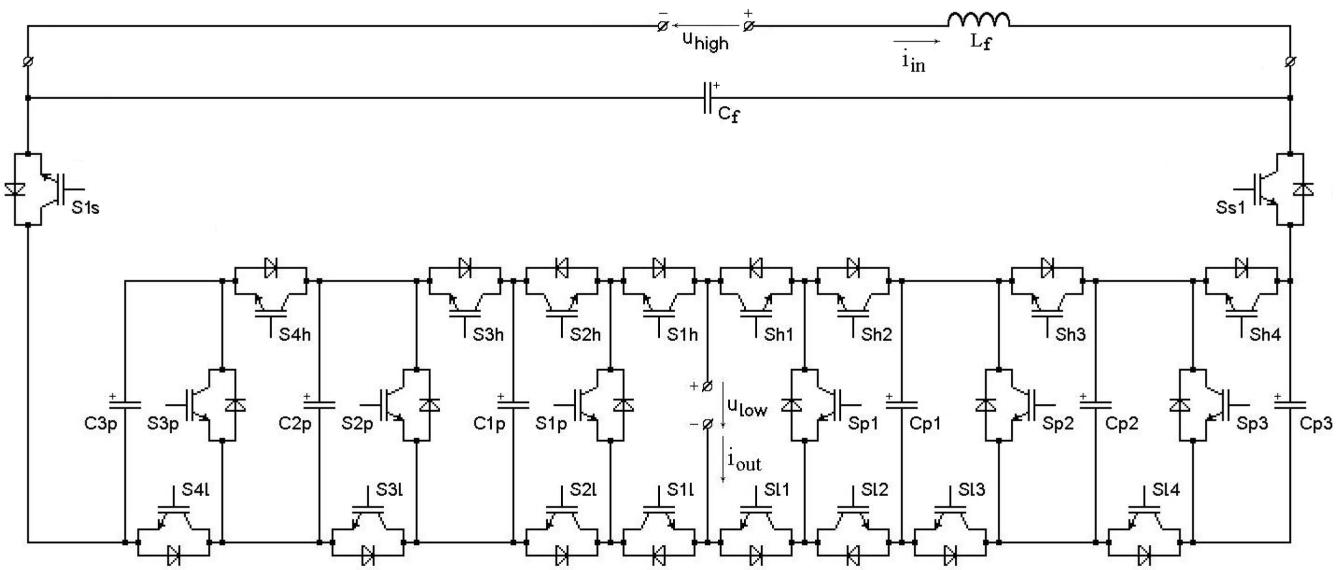

Fig. 2. Bidirectional six-stage dc-dc converter for an advanced DC electric locomotive

During the even PWM subinterval, a voltage is imposed on the load by connecting of three capacitors (to the right or to the left of load) in parallel, each with a voltage of 3 kV, to the dc machine load at u_{low}. Capacitors are discharged by this drive operation load current. The three opposite capacitors are used as ballast for imposing of surplus voltage.

The mathematical model of such a converter has been realized in program PSIM. The traction network of the future railways is represented by an EMF source of 18 kV (DC) with series resistance and inductance. The actual distance between traction substations will be about 50 - 60 km (now only 13-14 km) and that creates good impedance for converter operation. Capacitors values have been selected with 1000 Microfarad at the maximal load power rating of 3000 kW yielding a dc machine load current at about 1000A.

Voltage u_{low} and current i_{out} diagrams for load at converter output, diagrams of converter input current i_{in} and capacitor voltage u_{Cp1} can be seen in Fig. 3 for drive mode and in Fig.4 for recuperative braking. Here the diagrams for the capacitor voltage are given with a higher resolution.

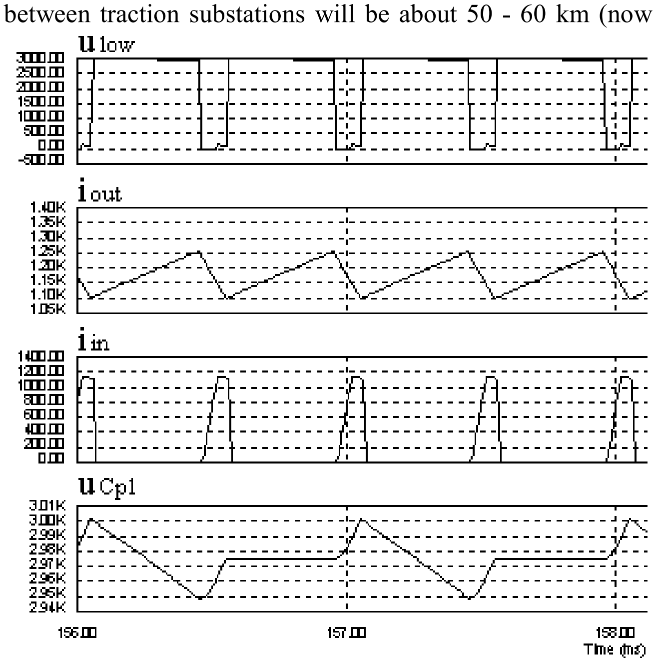

Fig. 3. Converter voltages and currents at drive mode

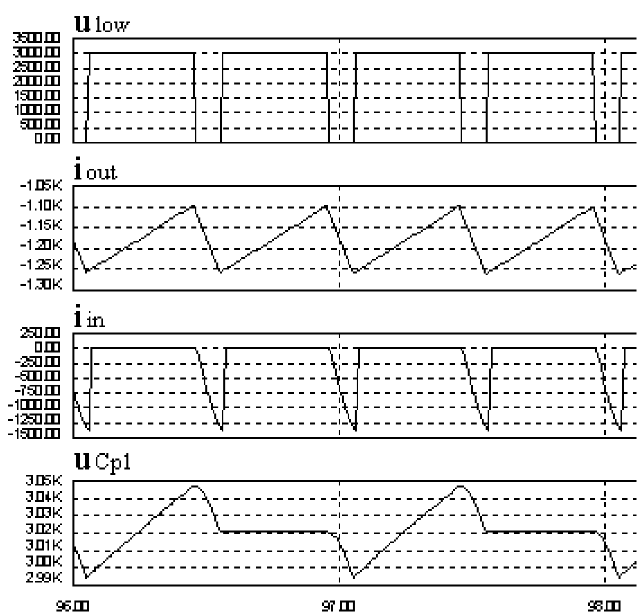

Fig. 4. Converter voltages and current at recuperation

Diagrams obtained from PSIM model are based on the parameters of a traction network corresponding to a position of an electric locomotive in the middle between traction substations with a voltage of the engine of 2.4 kV (modulation index at PWM is about 0.8).

Time course of voltages on all semi-conductor devices has been investigated, too. These voltages did not move out of the interval between 3.0 – 3.6 kV. Due to above described control method, the maximum total voltage across the series connected to high voltage source switches Ss (here Ss1 and S1s) is reduced from u_{high} - U_{lowmax} = (N - 1) · U_{lowmax} (that corresponds to simultaneous discharge of all six capacitors) to $u_{high}/2$ - U_{lowmax} = (N/2 - 1) · U_{lowmax}. Here U_{lowmax} is the maximum value of u_{low}, N is the factor of voltage transformation (the total number of capacitors). Thus, for the proposed converter with N = 6, we use two such switches Ss1 and S1s with the maximum voltage across each of them at approximately U_{lowmax}.

Quality of current of the traction engine is provided with a consecutive smoothing reactor in addition to the sum of two internal inductances included in the traction engines. Electromagnetic compatibility of the converter with a traction network is provided through additional input filter L_fC_f. The presence of the external filter reactor L_f is not compulsory due to the traction network inductance (about 1 mH per kilometer) that fulfills its function.

At regenerative braking mode (Fig. 4) - when the EMF of the traction machine is greater than the average value of a PWM voltage of the converter - the current in motor circuit decreases during active part of duty cycle, charging capacitors of the converter connected in parallel by corresponding switches.

A different algorithm of control of the proposed structure is possible for drive mode when series connected capacitors are charging through the branch of load by the chain Cp3-Cp2-Cp1-u_{low}-C1p-C2p-C3p. This allows avoiding the inclusion of the supplementary charge reactor at the converter input.

Realization of a 10 kW model unit of the proposed type of converter has been already started. During the next months this laboratory model converter rated at about 10 kW will be finished und practical results shall be present for ECCE 2010 congress.

RESULTS OF ANALYSIS AND SIMULATION

The analysis of discrete model of the converter in the drive mode is executed for the control algorithm with a charging of capacitors through a load branch. The diagrams for output voltage u_{low} and voltages across capacitors of the right-hand side (u_{Cp1}, u_{Cp2} and u_{Cp3}) and of the left-hand side (u_{C1p}, u_{C2p} and u_{C3p}) of the converter circuit are shown at Fig.5. Here n and γ_k (at k=1…7) are the order number and the fractional parts of the period of

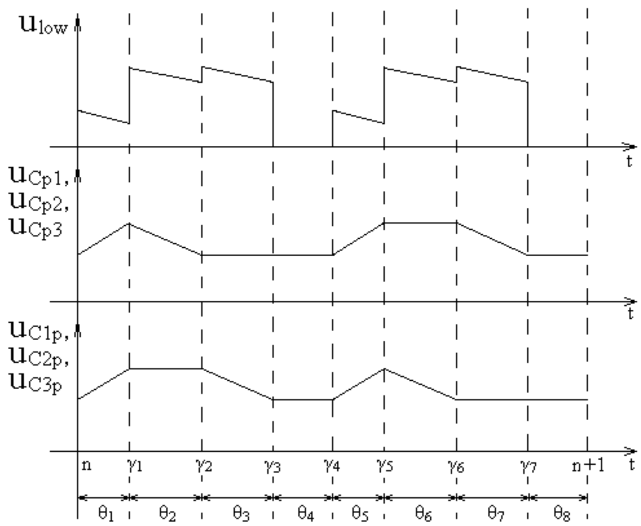

Fig. 5. Converter output voltage and voltages across capacitors in the drive mode

the electromagnetic processes in the converter (their dimensions is discrete time);

θ_1… θ_8 are time intervals (θ_1 and θ_5 are intervals of charging of all the capacitors, θ_2 and θ_7 are intervals of discharging of all the right-hand side capacitors, θ_3 and θ_6 are intervals of discharging of all the left-hand side capacitors, θ_4 and θ_8 are intervals of pauses with shorting of the load terminals).

The result of application of the method of the difference equations is the following formula:

$$U_{Cp}(n) = A^n \cdot e^{-\delta \cdot \theta \cdot n} \cdot U_{Cp}(0) + B \cdot \frac{1 - A^n \cdot e^{-\delta \cdot \theta \cdot n}}{1 - A \cdot e^{-\delta \cdot \theta}}. \quad (1)$$

Here $U_{Cp}(n)$ is discrete value of the voltage across each capacitor of the right-hand side of the converter circuit (u_{Cp1}, u_{Cp2} and u_{Cp3}), $U_{Cp}(0)$ corresponds to the period with zero order number;

A and *B* are constants depending on the parameters of the converter circuit;

δ is the damping constant of the eigentone of the load circuit, $\delta = \frac{R_{load}}{2 \cdot L_{load}}$, R_{load} and L_{load} are the parameters of the DC motor equivalent circuit;

$\theta = \theta_1 + \theta_2 + \theta_5 + \theta_7$.

Equation (1) allows estimating the final value and the peak-to-peak ripple of the capacitors voltages. So the needed values of capacitances can be easily calculated.

Fig. 6 presents the theoretical time dependence (corresponding to (1)) of the voltage across the capacitor $U_{Cp}(n)$ of the right-hand side of the converter circuit.

The two-quadrant load characteristics, obtained as a result of PSIM simulation of the proposed converter at both drive and recuperation modes, are shown at Fig. 7. Here γ is pulse duty factor, $\gamma = t_p/T_p$, t_p and T_p are pulse duration and pulse repetition period of output voltage.

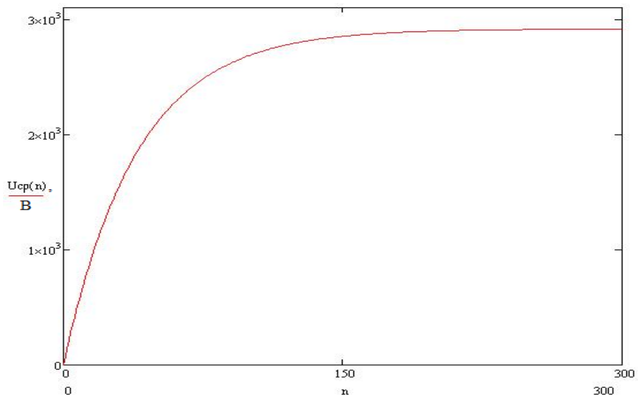

Fig. 6. The theoretical time dependence of the voltage across the capacitor

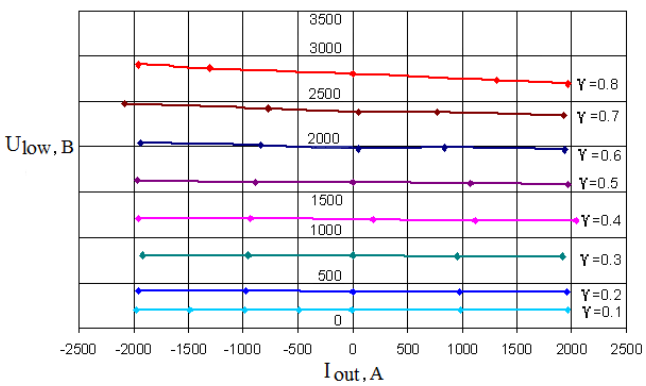

Fig. 7. The two-quadrant load characteristics of the converter

The PSIM simulation under the 1 kHz output pulse repetition frequency has shown that the semiconductor switches power losses are about 5 to 6 % of active output power.

IMPLEMENTATION OF THE GALVANIC SEPARATION OF THE LOAD

The power circuit of the above described converter has no galvanic separation between a grid line voltage of 18 kV and load where we form voltage up to 3 kV. The absence of a galvanic separation is dangerous as at occurrence of emergency mode at the converter operation when unlocking of all power switches will lead to hit loading under voltage of 18 kV, as from the point of view of safety of serving staff at carrying out of repair or service of motors at the lifted current collector.

The galvanic separation of the load can be implemented by the adding of four alternating current valves Sf1-Sf4, the reversible rectifier R and the output transformer, operating at raised frequency, into the circuit of the proposed converter, as it is presented at the Fig. 8.

The simulated plots of the voltages across the capacitors u_{C3p} and u_{Cp3}, the voltage of the primary winding of the transformer u_1 and the output voltage and current of the bidirectional six-stage dc-dc converter with galvanic separation of the load are shown at the Fig. 9.

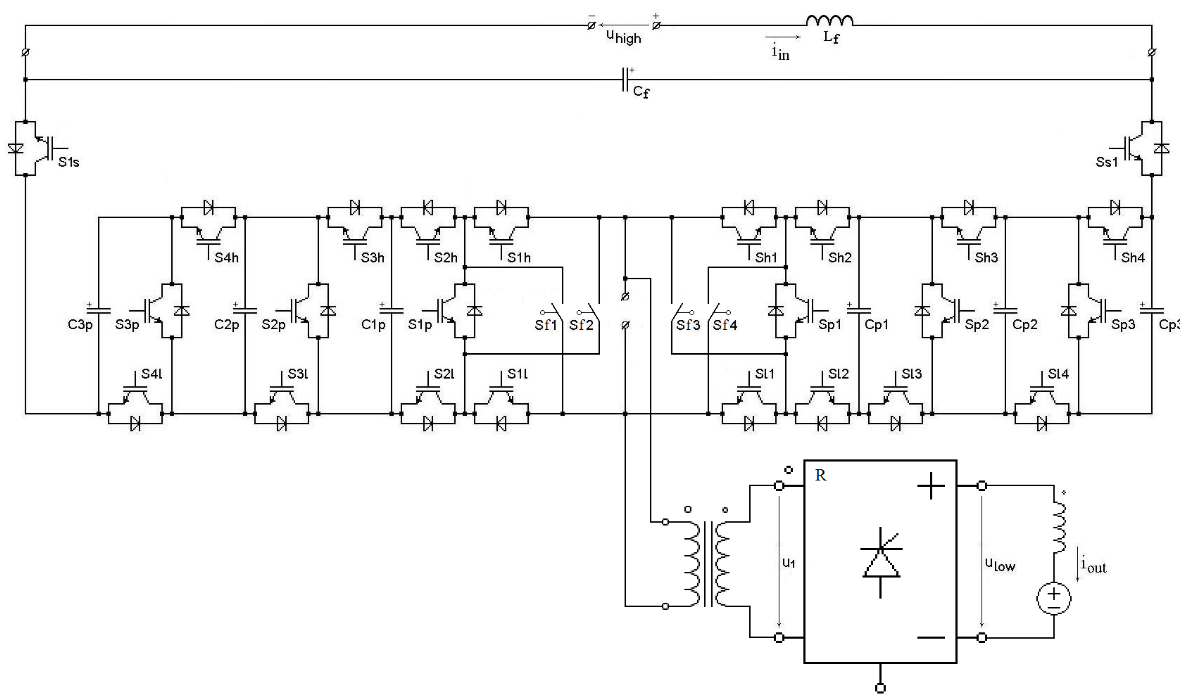

Fig. 8. Bidirectional six-stage dc-dc converter with galvanic separation of the load

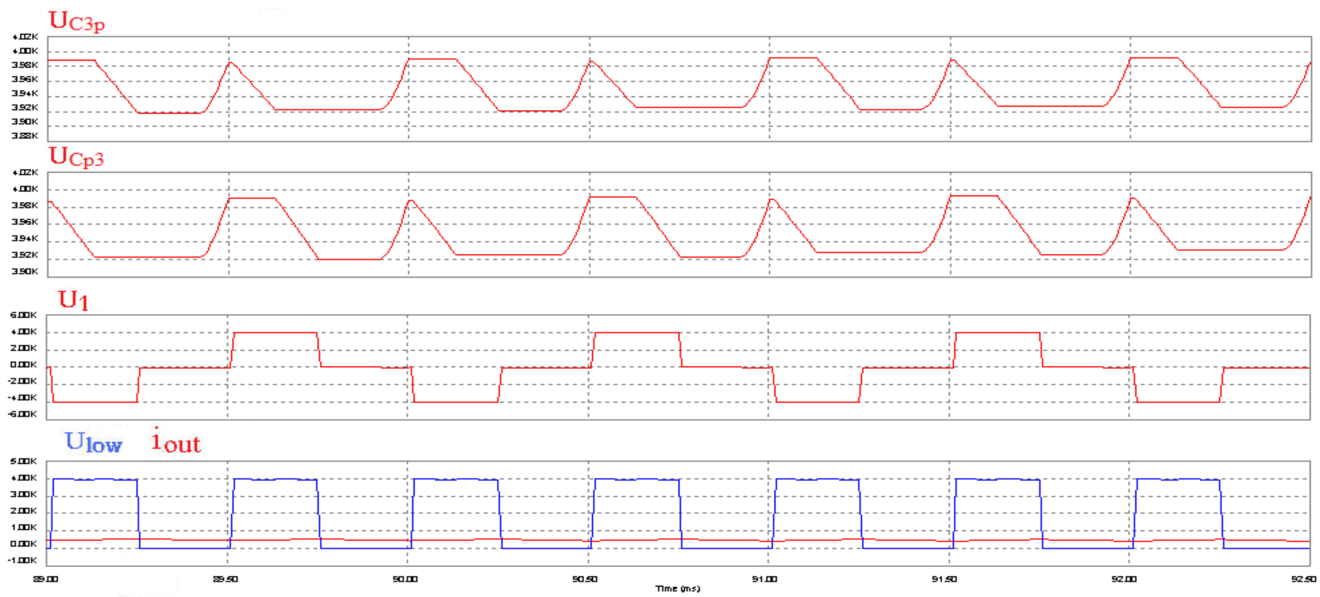

Fig. 9. Voltages across the capacitors, voltage of the primary winding of the transformer and output voltage and current of the bidirectional six-stage dc-dc converter with galvanic separation of the load

The voltage across the primary winding of the transformer has an insignificant constant component, which in practice can lead to the magnetic bias of the transformer. The closed-loop control with the tracking of the capacitors voltages is able to get rid of a constant component in target voltage. We can also reduce it by the tuning of duration of the discharge interval of the capacitors.

CONCLUSION

A special high-voltage bidirectional step-down dc-dc converter is proposed which is intended for connection of power trains of existing direct current electric locomotives (3 kV, 1.5 kV, and 0.75 kV) with future traction networks running on much higher direct voltage at existing railways. We enable the system to handle a voltage in the catenaries which is n-times as much than the voltage of the machine drive circuit in the electric locomotive. Here, n is the number of cells in the converter. An increase of the direct voltage in a network up to 12 kV, 18 kV, maybe even 24 kV, or 30 kV, provides the same advantages to DC traction which AC high-voltage traction (15, 25, or 50 kV) already has but without the specific AC disadvantages.

With this proposed novel converter, the voltage at all components of the circuit is defined by the voltage of drive motor equipment of this locomotive avoiding any problem of balancing the voltage at capacitors. Further on, this proposed converter can be connected to a voltage source inverter driving three-phase traction induction motors.

The other advantages of the proposed converter are the abilities of the two different control algorithms for the drive mode and the implementing of the load galvanic separation by using the raised frequency output transformer.

REFERENCES

[1] V. E. Rozenfeld, V. V. Shevchenko, V. A. Maiboga, and G. P. Dolaberidze "High voltage direct current system with thyristor converters on locomotives," *Electrical Engineering*, 1968, № 3, pp. 4-6.N. A. Phridman and N. N. Demchenko, "6 kV direct current in railway network," *Railway Transport*, 1976, № 1, pp. 87-90.

[2] N. Hugo, P. Stefanutti, and M. Pellerin, "Power Electronics Traction Transformer," in *Proc. EPE07*, Aalborg, 2007, CD, file 0715.pdf.

[3] M. Steiner and H. Reinold, "Medium Frequency Topology in Railway Applications," in *Proc. EPE07*, Aalborg, 2007, CD, file 0585.pdf.

[4] Railway mechanical engineering, Review of branch, RBC, February 2003,27p.[Online].Available:http://www.ecsocman.edu.ru/images/pubs/2004/06/27/0000164043/Zheleznodorozhnoe_mashinostrenie.pdf.

[5] V. A. Malyutin, V. V. Litovchenko, *et al.*, "The analysis of the construction of the traction and auxiliary converting equipment of the modern railway operating stock," in Electric traction at the boundary of centuries, *Proc.* under the editorship of A. L. Lisitsyn, Moscow, Intekst, 2000, 256 p.

[6] *Strategy of Development of Russian Railway Transport up to 2030,* Governmental order 877-p from 6/17/2008.

[7] M. I. Bader, U. M. Inkov, V. P. Pheoktistov, and N. G. Shabalin, "Condition and prospects of the development of Russia electrical railway transport to first half of XXI century," *Izvestiya of Russia Electrotechnical Academy,* 2008, № 1, pp. 81-92.

[8] G. S. Zinoviev, N. N. Lopatkin, and N. I. Schurov, "High-voltage bi-directional dc-dc-converter for the future electric locomotives," in *Proc.* of the *Transport – 2009* All-Russia scientific and practical conference, Rostov-on-Don, 2009, Part 3, pp. 215-217.

[9] N. N. Lopatkin, G. S. Zinoviev, and H. Weiss, "High-voltage bi-directional dc-dc-converter for advanced electric locomotives," in *Proc.* EPE 2009, Barcelona, Spain, 2009, CD, paper 1066.

[10] G. S. Zinoviev, N. N. Lopatkin, and H. Weiss, "High-voltage dc-dc-converter for the new wave electric locomotives," *Electrical Engineering*, 2009, № 12, pp. 46-51.