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

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Keywords

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Abstract

Existing DC current high power locomotives at standard input voltages of 3 kV, 1.5 kV, or 0.75 kV can be connected to high-voltage catenaries operated at n - times the DC voltage level via a novel n-cell capacitor switching converter. Each cell voltage is defined by the locomotive power train DC input level, thus balancing of capacitor voltages is not required.

1.- Introduction

Due to its earth-connected supply and (naturally) earth connected load, high power ratings, and demands on low weight and volume, electrical supply of railways is a special system. Advanced power electronics circuits provide advantages for these systems.

Today, two basically different systems of electrification of railways co-exist in the world. We find direct voltage systems (mainly on 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 with the DC traction machine as well as with three-phase AC traction machines (more often induction machines than synchronous machines), have no problems through asymmetrical loading of the feeding three-phase power supply system but have obvious restrictions on power because of a low voltage at the contact network at the catenaries. In the sixties of last century tests of thyristor-capacitor systems for electrification were carried out in Russia [1], [2]. In the seventies, test were carried out in Italy [3] with 6 kV DC. However, these experiences have not led to a new concept for DC electric locomotives due to unavailability of powerful insulated-gate-bipolar-transistors and gate-turn-off-thyristors at that time.
Therefore, the most powerful electric locomotives have been designed for single-phase AC electric supply systems with rated voltages of 25 kV (RMS) respectively 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.
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) [4] or (relatively) high frequency (18 kHz) [5]. Now the increase in power of a future electric locomotive is not limited to weight and dimensions of the transformer.
The transformer, however, was just the means for providing an interface between high transmission voltage and considerably lower load voltage, and being the actuator for speed and power control by allowing a simple change in load voltage by transformer taps as used for old locomotives. Nowadays, designs without transformer are feasible through special power electronics circuits. General demands are high input voltage in a wide range and rather smooth currents along with recuperation opportunity. Extensive filter circuits are to be avoided.
New technical designs without transformers for step-down or step-up dc-dc converters 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 Tab. 1 according to International Rail Statistics [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
Germany	7,0	21,0	131,4	19,8
France	5,0	15,7	455,1	9,1

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 [8] 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 [7]. 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).

2.- Considerations for Locomotive Power Converters without Transformer

In order to visualize the basic concept for power conversion without transformer on DC locomotives we first compare a standard step-down (Buck) converter (Fig. 1) to a switched capacitor solution (Fig. 2).

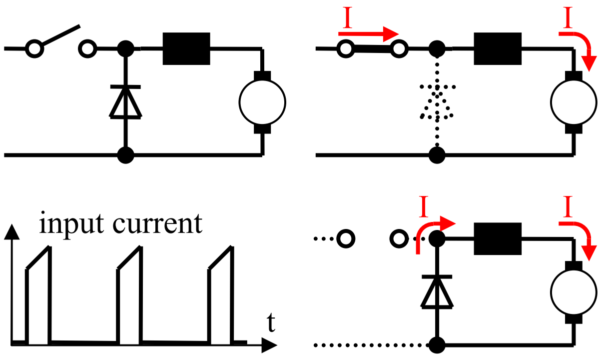

Fig. 1: Buck converter, active topologies, and time course of input current for duty cycle = 0.25

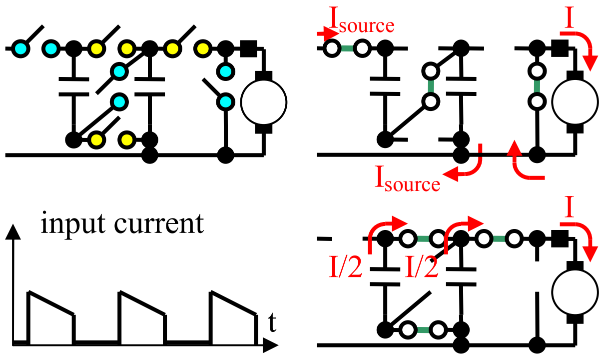

Fig. 2: Simplified switched capacitor converter and schematic time course of input current

We convert 12 kV at the catenaries into 3 kV for the load represented by a DC motor. We see large input current pulses for the Buck converter (Fig. 1) due to the required duty cycle of 0.25. During the active phase, the load current is equal to the input current. In freewheeling mode, the load circuit is separated from the source but still has a common ground connection.
The simplified switched capacitor converter (Fig. 2) is composed of a much higher number of switches. Three of them (denoted by blue color) are in “on-state” during the grid supply phase with the two capacitors in series connection while the load is in freewheeling mode. The other three switches (denoted by yellow color) are in “on-state” during the active part for power transfer into the load realizing a parallel connection of the capacitors to the load and an appropriate high current capability and peak load voltage of one half of catenaries voltage. Current shapes are for illustration only and need not be coincident to actual ones. However, we see that the duty cycle now is defined by the required voltage at the load with respect to capacitor voltage which is now one half of catenaries voltage.
In this first approach at Fig. 2, for simplicity reasons we selected only 2 capacitors, we did not go into details for realization of the switches, and we did not consider recuperation mode.

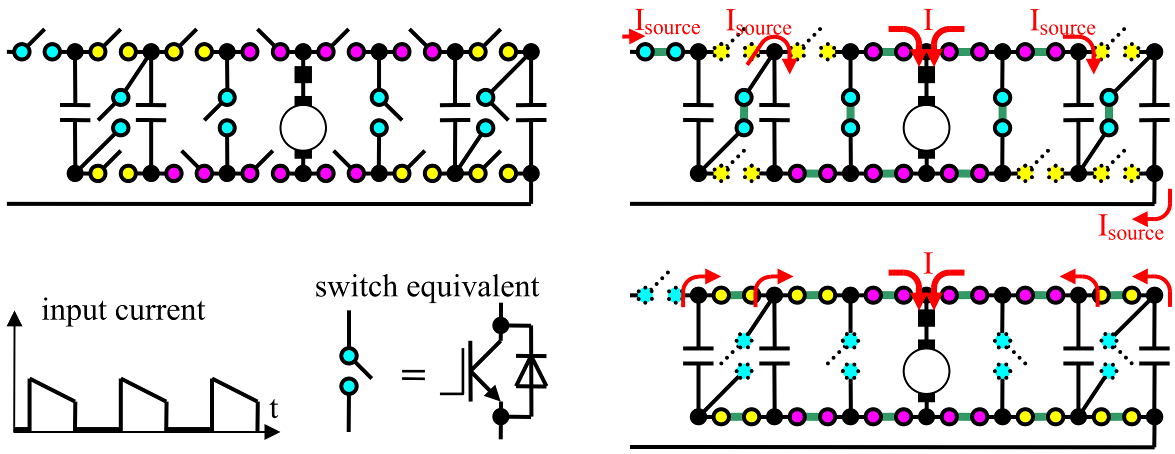

Fig. 3: Special four-capacitor converter with switch realization by IGBT and anti-parallel diode

In a next step, we increase the number of capacitors in series connection to 4 (Fig. 3) in order to obtain higher voltages feasible at the catenaries side at given load side peak voltage. For our special aim of restricting peak switch voltage to u_{out} level, we select a symmetrical layout for this investigation and shall find the load at a potential of about one half of input voltage.
Our first approach is a symmetrical operation of the switch array. However, this would lead to a voltage stress at input side switch (Ss in Fig. 5)
For standard power transfer from catenaries to motor, some switches change their state in order to accomplish series connection of capacitors (power from catenaries, blue switches “on”), or parallel connection (power into motor, yellow switches “on”), respectively.
However, in this first approach of switch control there are switches integrated in the circuit denoted by violet color which are “on” all the time during drive mode (power flow from catenaries to motor). These switches get a special function for keeping all switch voltages at capacitor voltages at defined maximum and for proper recuperation mode when power is transferred from the machine acting as generator into the catenaries. Then the lower voltage at the motor armature windings (lower induced voltage due to lower speed) has to be stepped-up into a higher capacitor voltage in active phase of motor converter. In the subsequent phase, the series-connected capacitors are discharged into the catenaries line.
Modern locomotives are equipped with recuperation (active breaking, regenerative braking) capability as standard.
Realization of the switches has to follow the rules of simplicity and ruggedness. By establishing switches around the capacitors and controlling the converter in a proper way we keep the blocking voltage at each switch within range of capacitor voltage and may use diodes for reverse current conduction when necessary. Therefore, we generally have to avoid true bi-directional switches which exhibit active blocking for both polarities of voltages and both polarities of currents. We shall simply use single-polarity switches (see Fig. 3) which can be turned on for one current direction and carry current for other direction by anti-parallel diode, and maintain a uni-polar (blocking) voltage applied on the switch.
Also the circuit should be kept simple. Under investigation is a simple series-charging circuit. The current waveform at the catenaries may be a disadvantage but a much more complex circuit is avoided that eventually could implement a boost function and a naturally continuous current shape.

3.- 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 12-18kV or even above.
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 3kV level equipped with direct current traction engines (electric locomotives of type EP1, EP2k, Fig. 4), and with asynchronous traction engines (electric locomotives of type EP10, EN3).
The DC-link voltage of the voltage-source PWM-fed locomotives can be considered equivalent to the armature voltage of standard DC motors. The same converter with IGBT-transistors with twice smaller voltage can be used for electric locomotives operating at a constant voltage of 1.5kV. In the scheme considered with four capacitor-transistor cells and with IGBT-transistors of 3.3kV, 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, …, cells can work at a contact network voltage level of 9 kV, 12 kV, 15 kV, … kV.

Fig. 4: New Russian DC locomotive EP2k

4.- Circuit Schematic and Operation Principle of Special 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 4 times the target voltage (at a 4-cell dc-dc converter), or even 6 or 8 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 mostly overcomes this basic problem. Practically, the voltage at almost any element of the converter does not exceed the output voltage of the converter at any number of voltage transformation factors. The only exception (for a voltage transformation factor greater than 4) is the IGBT-switch, series connected between dc traction network and capacitor cells. The converter is based on the concept of the "Marx Converter" [9] by operating all capacitors of the converter at series connection when switched to the high voltage of catenaries network u_{in} and their subsequent parallel connection at their discharge state supplying the load at low voltage u_{out}. 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 are eliminated which provide discrete voltage steps to traction engines. Now a smooth regulation of the direct voltage at the traction engines is performed 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 converter circuit is displayed in Fig. 5.

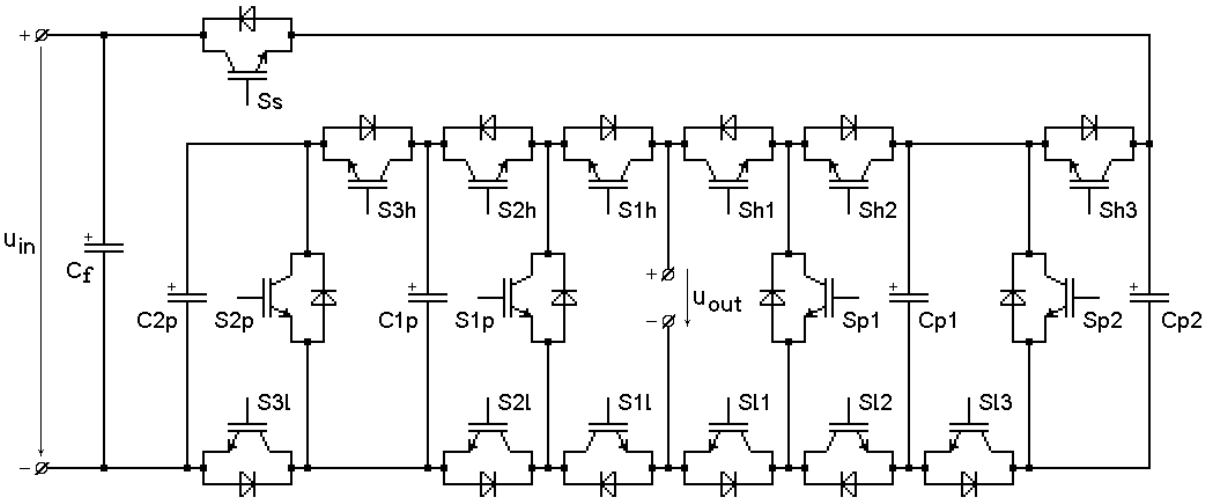

Fig. 5: Bidirectional four-stage dc-dc converter for an advanced DC electric locomotive

In our case, four capacitors Cp2-Cp1-C1p-C2p by their consecutive inclusion through control of corresponding IGBT-transistors (6.5 kV rating) are charged in series connection by u_{in} at total contact network voltage rating equal 12 kV up to a voltage of 3 kV for every capacitor. The inductive load current at u_{out} becomes separated from charging circuit through inverse diodes of transistors Sl1, Sp1, Sh1 and S1l, S1p, S1h, respectively, performing the function of freewheeling diodes. The PWM zero subinterval of the load voltage is formed through these parallel paths.
During the active output PWM subinterval, a voltage is imposed on the load by connection of two capacitors in parallel (Cp2 and Cp1 to the right or C2p and C1p to the left of load), each with a voltage of 3 kV, to the dc machine load at u_{out}. Capacitors are discharged by this drive operation load current. The two opposite capacitors are used as counter-voltage in order to keep the off-state voltage on switch below a given limit. So the maximum voltage across the switch Ss is reduced from $u_{in} - U_{outmax} = (K - 1) \cdot U_{outmax}$ (that corresponds to simultaneous discharge of all four capacitors as described by control scheme in Fig. 3) to $u_{in}/2 - U_{outmax} = (K/2 - 1) \cdot U_{outmax}$.

Here, U_{outmax} is the maximum value of u_{out}, and K is the factor of voltage transformation. Thus, for the proposed converter with K = 4, the maximum voltage across switch Ss is approximately U_{outmax}.
For a simulation at system level, the mathematical model of such a converter has been realized in program PSIM. The traction network of the Russian Railways is represented by an EMF source of 13.2 kV (DC) with series resistance and inductance. The actual distance between traction substations is about 13 - 14 km and that creates good impedance for converter operation. Circuit capacitors values have been selected with 1000 Microfarad at the maximal load power rating of 3000 kW yielding a corresponding dc machine load current at about 1000A.
Load voltage (1) and load current (2) diagrams for load at converter output, capacitor voltage (3) and converter input current (4) can be seen in fig. 6 for drive mode and in fig. 7 for recuperative braking, here with a higher resolution for the capacitor voltage u_{cp1}.

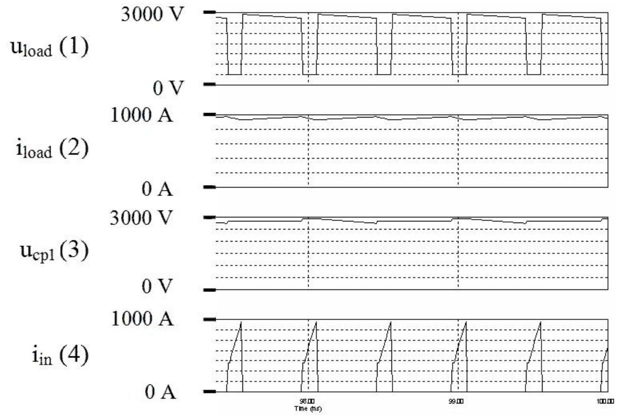

Fig. 6: Time course of converter voltages and currents at drive mode

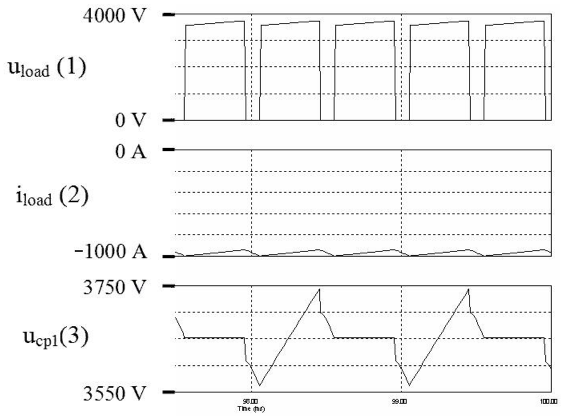

Fig. 7: Time course of converter voltages and current at recuperation mode

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 2.8 kV (modulation index of PWM about 0.88). Time course of voltage on all semi-conductor devices have been taken off also. They did not leave the interval between 3.0 – 3.6 kV. Quality of a 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.
Interference to the catenaries voltage is neglected in this system study. A standard solution to reduce pulse-shaped currents widely is to use 2 subunits being operated in a 180-degree phase-shift mode of control. E.g. for a duty cycle of 0.5 (50 %) for each subunit we get low pulse content of catenaries current. When we have first subunit in power draw mode from grid we drive second subunit in motor power draw condition. Then we switch between operation modes of the two converters of the locomotive, and now catenaries current flows into second subsystem.
Such a subsystem is evaluated by means of PSIM program.
Generally, locomotives will have additional filter circuits on board. Electromagnetic compatibility of the converter with a traction network is provided through additional input filter LfCf. At regenerative braking mode (Fig. 9), 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 all capacitors of the converter connected in parallel by corresponding switches.

5.- Comparison of Proposed Converter to Four-Level FC DC-DC converter

A different solution for the DC-DC conversion under discussion is the standard approach using a four-level floating capacitor (FC) DC-DC converter (Fig. 8) [9]. This converter (Fig. 8) is the reference and comparison basis for evaluation of the proposed circuit from Fig. 5.

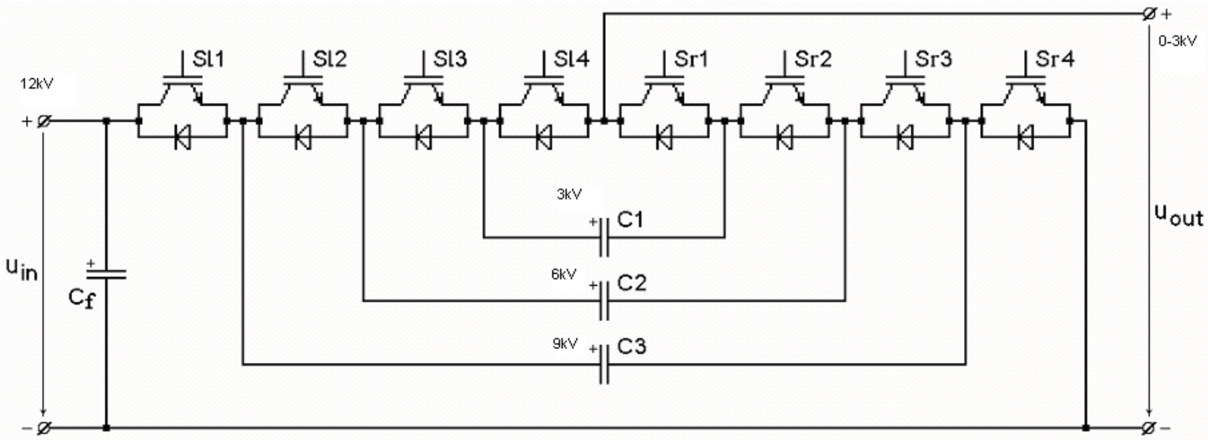

Fig.8: FCC-based bidirectional dc-dc converter for traction application with K = 4

In order to guarantee (alike to the proposed dc-dc converter presented in Fig. 5) the maximum values of voltages across all the switches being equal to the output voltage the capacitors voltage follow-up control can be used.

The comparison between the two variants of bidirectional dc-dc converters was performed for a converter proposed in Fig. 5 using a special control algorithm that essentially differs from the previously described one. The capacitors' charging through the load was used to avoid a problem of limitation of capacitors' currents. The conventional solution for this problem requires a heavy complication of dc-dc converter circuitry. Thus, the algorithm used here is of obvious interest.

Plots of simulated output voltages and currents of two variants of bidirectional dc-dc converter are shown in Fig. 9 and Fig.10.

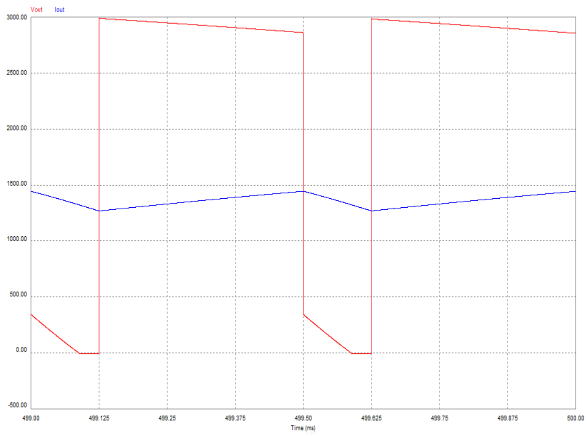

Fig. 9: Time-course of output voltage and current of proposed variant of dc-dc converter under specified control

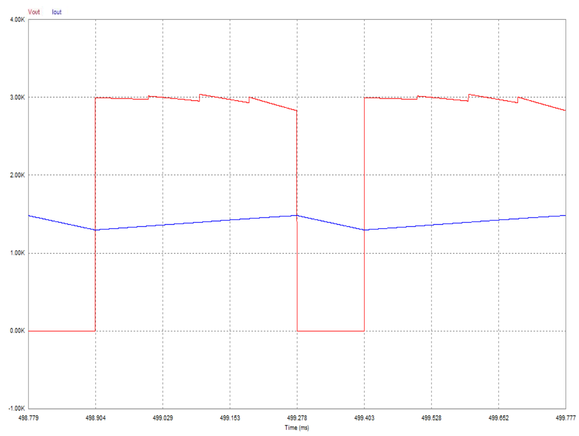

Fig. 10: Time-course of output voltage and current of FC C-based dc-dc converter under specified control

The parameters and conditions of PSIM simulation and its comparative results are presented in Table I and Table II, respectively.

Table II: Parameters and conditions for PSIM simulation

Traction network and input parameters				Load and output parameters					
E_{in}, kV	R_{in}, Ohm	L_{in}, μH	C_f, mF	E_{out}, kV	R_{out}, mOhm	L_{out}, mH	T_p, ms	γ	$F_{r\text{-}iout}$
12	0.4	7	1	2.11	82	1.5	0.5	0.75	0.05

E_{in}, R_{in} and L_{in} are the EMF, the resistance and the inductance of traction network, respectively. C_f is the capacity of the input filter; E_{out}, R_{out} and L_{out} are the EMF, the resistance and the inductance of the load; 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; $F_{r\text{-}iout}$ is ripple factor of output current.

Table III: Results of comparison between two variants of bidirectional dc-dc converters

RSI_{0T}	RSI_T^2	RSI_{onT}	RSI_{offT}	RSU_{C0}^2	$RSCU_{C0}^2$	RSI_C^2
0.366	0.412	1.161	1.483	3.573	4.594	1.034

Here RS*X* is the quotient (ratio) of the sum of quantities X related to switches or capacitors (having identical losses parameters) of standard FC C-based dc-dc converter and the similar sum of proposed variant of dc-dc converter. The quantities in the capacity of *X* are specified below:
I_{0T} and I_T are the average and the RMS values of the transistor current, respectively;
I_{onT} and I_{offT} are the sums of non-zero transistor switching currents of each switching during one pulse repetition period of output voltage, for switching on and switching off, respectively;
U_{C0}^2 and RSI_C^2 are the squared average voltage and the squared RMS current of capacitor;
CU_{C0}^2 is the squared average voltage of capacitor multiplied by its capacity.

6.- 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 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 as 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 engines with alternating currents.
Compared to a (four-level) floating capacitor dc/dc converter, we obtain the following results:
1. Energy of capacitances ($CU^2/2$) in proposed circuit is 4.5 times less than in the scheme of the dc-dc converter with floating capacitors. The proposed scheme essentially reduces expenses for capacitances and does not exhibit problems with stability of voltage distribution on capacitors.
2. The sum of squares of currents (which defines conduction losses in these switches) for proposed converter is approximately 2 times higher over all transistors and less at all diodes compared to the circuit with floating capacitors.

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