

PAPER

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Bidirectional DC-DC conversion device use at system of urban electric transport

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Abstract. The paper considers questions of energy storage devices used in electric transport, especially in the electric traction drive of a trolley bus, in order to provide an autonomous motion, overhead system's load leveling and energy recovering. For efficiency of the proposed system, a bidirectional DC-DC converter is used. During the simulation, regulation characteristics of the bidirectional DC-DC converters were obtained.

1. Introduction

In the transport industry, including urban electric transports, the use of energy storage devices becomes relevant with relation to development, existing energy storage devices' application in the electric energy system and increasing the energy efficiency of the electric transport complex. Also, the energy storage devices' implementation to the trolleybus traction drive makes it possible to prolong the vehicle's routes in urban settings without the building of additional mains supplies that provides secluded city districts with green transport at the least costs. In addition, energy storage devices can solve the problems not only of traction drive's self-contained supply, but also of smoothing out peak loads in overhead systems, receiving energy recovery, etc.

Currently, the most efficient energy storage devices are supercapacitors. In the proposed traction drive, a bidirectional DC-DC converter is used as a connecting link between the electric energy storage device, the electric motor and the overhead system [1].

2. The chain diagram of the energy efficient trolley electric drive

The chain diagram of the energy efficient trolley electric drive's power contour is shown in figure 1, where U_1 – DC supply voltage; U_2 – output voltage of DC-DC converter or energy storage device; PWM-VSI – self-commutated voltage inverter with pulse-width modulation; VD – diod; VT – IGBT transostor; R_B – braking resistor; M – AC motor.

The typical power layouts of AC motor from DC supply consist of a self-commutated voltage inverter with pulse-width modulation (PWM-VSI) [2, 3]. It allows to implremnt the frequency and vector control algorithms of an AC motor with a velocity transducer and without it [4, 5]. A self-commutated voltage inverter consists of six fully-controllable IGBT transistors and DC buffer link (C1). There is a smoothing-inductor (L1), which limits the consumption currents and voltages pulsation. In addition, the inductor is necessary to limit the rate of current rise in case of a short-circuit, which makes a safety automatic disconnection. A diode (VD1) is required to cut off the recuperation of braking energy to the network for reason that the traction substations' power rectifiers



are unidirectional. In the standard circuit, the external braking resistor (R_B) dissipates the braking energy. The VTB transistor switches on the branch of the resistor.

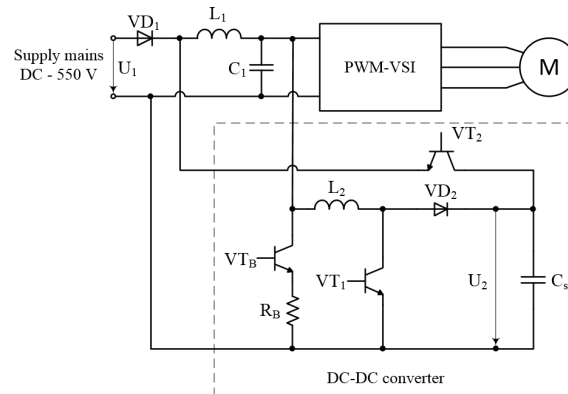


Figure 1. A functional diagram of the energy efficient trolley electric drive

To improve the energy efficiency of the trolleybus, a bidirectional pulse width DC-DC converter is included in the typical VSI circuit [6, 7, 10]. For vehicle modernization there are such advantages of pulse-width DC-DC converters as cheapness, easy implementation and small weight-size parameters, which are important. Such DC-DC converter consists of two operated alternately devices. First is the boost converter, which transforms DC link voltage (U_1) 550 V to higher voltage of the energy storage device (U_2) 550-1100 V, and it is made up of inductance L_2 , transistorized module VT_2 and bypass diode VD_2 . The second is a down converter which transforms the high voltage of the energy storage device of 1100-550 V into the 550 V voltage. As an energy storage unit, a block of electric double-layer capacitors (ionistors) is used, which has such advantages as high specific capacity (104...105 W/kg), the energy density (about 50 kJ/kg), a multiplicity of charge-discharge cycles (the range from one hundred thousand to one million), charge time (up to 30 sec), wide operating temperature ($-50...+100^\circ\text{C}$), high efficiency (more than 95%), long storage time of stored energy (hundreds of hours), practically unchanged discharge rate at all operating temperature [8, 9].

3. Mathematical description and functional chart of DC-DC converter actuating system

The operation of the first step-up DC-DC converter is formed from three time segments over a period that is shown in figure 2.

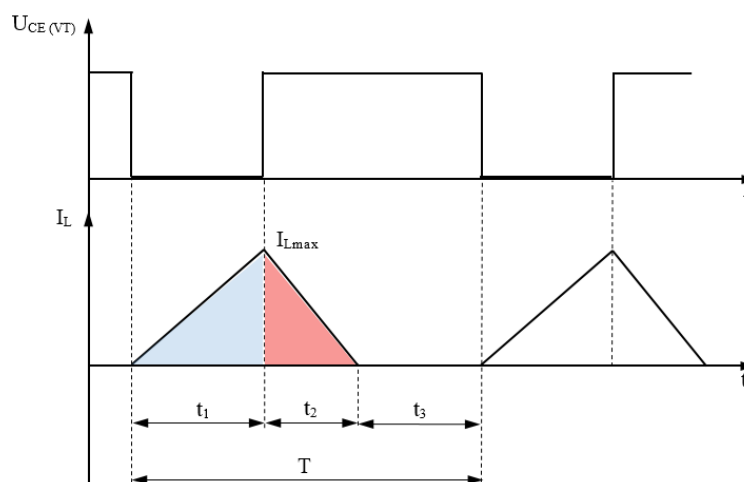


Figure 2. Voltage and current waveforms of a DC-DC Converter.

Transistor VT₁ is switched on during first time interval t₁. At this moment, inductance L₂ is connected to «+» and «-» of DC link C₁. The rate of current rises and its maximum value (I_{Lmax}) depends on the inductance value L₂ and the voltage value U₁. During second time interval t₂, transistor VT₁ has been switched off, and the flowing through the diode VD₂ current, accumulated in the inductance, charges the energy storage device C_s. The third time interval t₃ is no-current condition, when the diode VD₂ limits backflow leakage of the current from the energy storage device to DC link.

The operation of the DC-DC down-converter is similar to the boost converter; however, the transistor VT₂ commutes instead of the transistor VT₁, and the time interval t₁ is equal to t₂.

The average current of the DC-DC boost converter is:

$$I_{L2} = (U_1^2 \cdot \gamma^2) \cdot (2 \cdot (U_2 - U_1) \cdot f \cdot L_2)^{-1}, A \quad (1)$$

where $\gamma = t_1 \cdot T^{-1}$ – pulse ratio, T – period, f – VT switching frequency.

The average current of the DC-DC down-converter is:

$$I_{L1} = (U_2 - U_1) \cdot 2\gamma \cdot (f \cdot L_1)^{-1}, A \quad (2)$$

According to expressions (1) and (2), figure 3 shows the regulating characteristics of boost (a) and downfall (b) DC-DC converters, which are constructed with the following parameters: U₁=550 V; U₂=1100 V; L₂=10 μHY; L₁=100 μHY; f=6 khz.

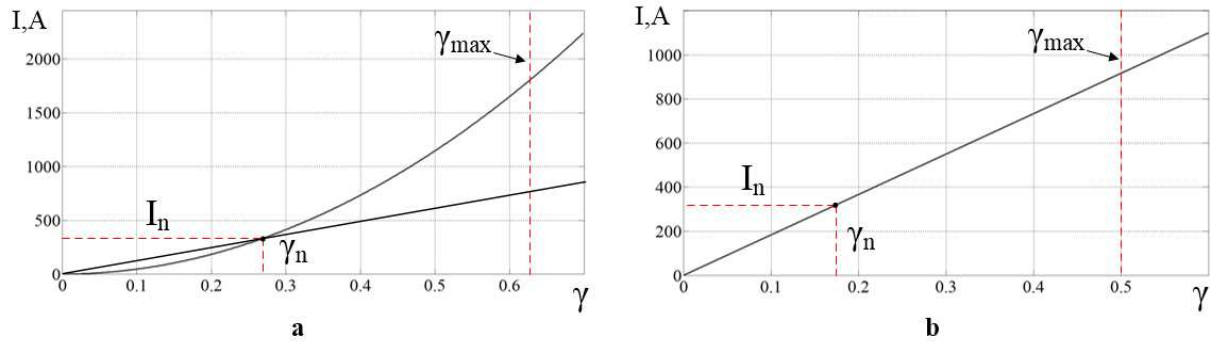


Figure 3. Regulating characteristics of DC-DC converters.

To simplify the controlling system calculation of the boost DC-DC converter, a linearization was made at rated values.

Figure 4 shows the current loop structure of the boost-and-down DC-DC converters.

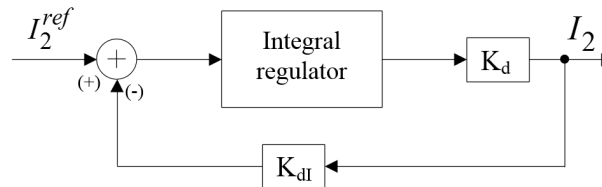


Figure 4. Circuit of DC-DC converters.

The integral gain of DC-DC converters is calculated based on the frequency-sharing condition:

$$k_i = \Omega_1 \cdot (K_d \cdot k_{dl_2})^{-1}, \quad (3)$$

where $\Omega_1 = 2\pi \cdot f \cdot k_{md}^{-1}$; k_{md} – motion division coefficient; f – switching frequency of transistor.

4. Control algorithm and digital simulation of energy-efficient trolleybus

The operation algorithm of the bidirectional DC-DC converter is based on the evaluation of the motor's torque sign that is shown in Fig. 5.

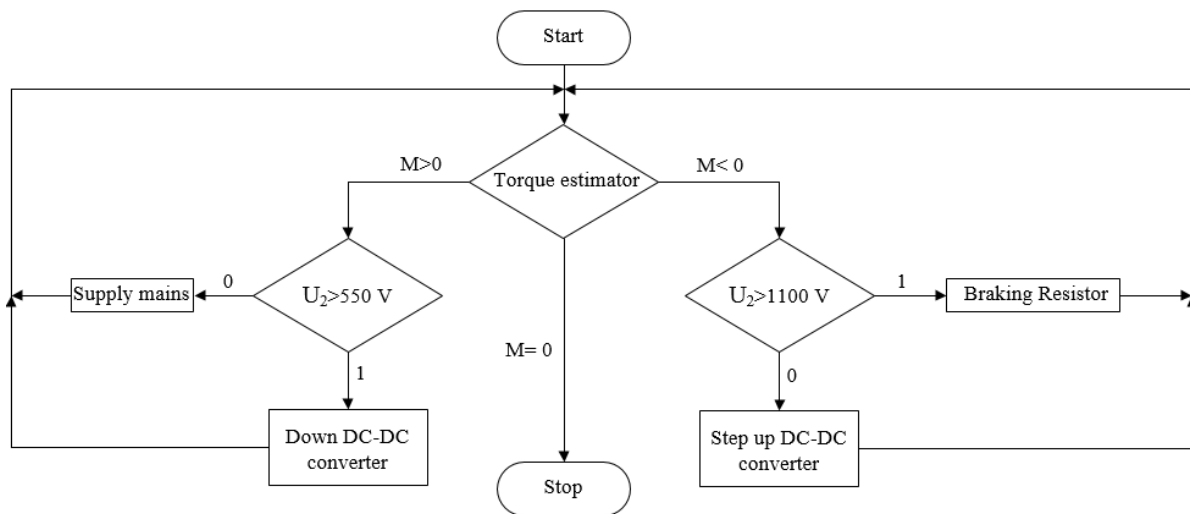


Figure 5. The operation algorithm of the bidirectional DC-DC converter.

If the motor torque is positive (accelerated mode and preset speed maintenance) and the voltage of energy storage device is more than 570 V, then the DC-DC down converter is switched on and no current is consumed from the power grid. In this case, the braking energy stored in the accumulator goes to the DC link of the VSI and is consumed by the electric motor. If the motor torque is negative (braking mode) and the voltage of energy storage device is less than 1100 V, then a DC-DC boost converter operates. The energy store maximum voltage is limited by value of 1100 V. When this voltage is reached, the VT_B transistor switches on, and the excess braking energy is dissipated into the resistor R_B .

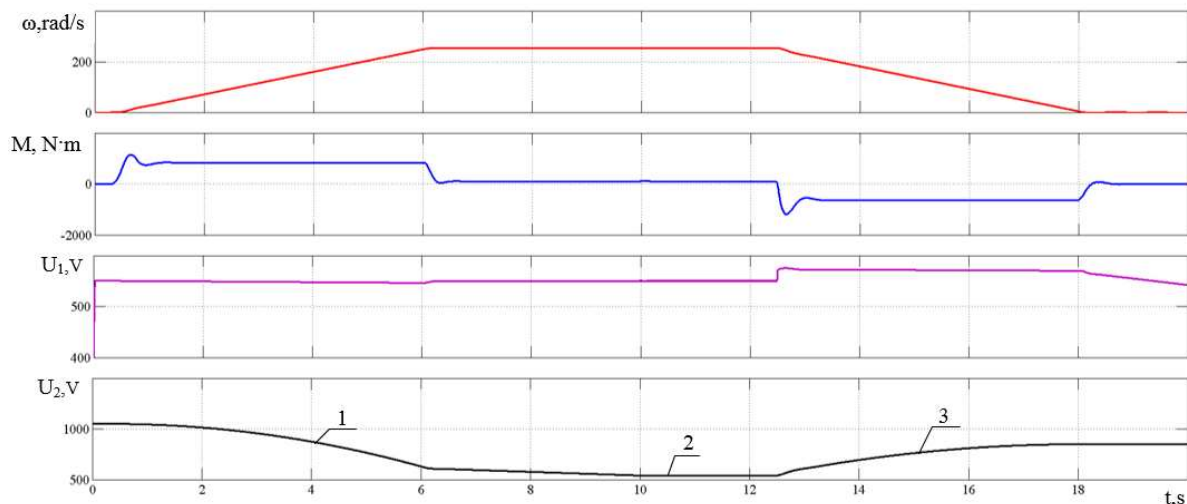


Figure 6. Transient processes of an energy-efficient electric motor drive: 1-discharge of an energy storage, 2- an electric drive operation from an overhead system and 3 - energy storage charging.

During the simulation, which was carried out in the Matlab/Simulink software package, the following system parameters were chosen: acceleration/deceleration time (7 sec); capacity of the energy storage device (2.5 F), power of an induction motor (200 kW), engine rated speed (1480 rpm). Figure 6 shows the transient processes of motor shaft speed, motor torque, DC link voltage and voltage of energy store.

5. Conclusion

The work deals with the operation of a bidirectional DC-DC converter. A functional scheme of energy-efficient power supply, a mathematical description of a bidirectional DC-DC converter, the operation algorithm of the electric drive and simulation modelling are proposed in the paper.

The proposed engineering solution for the trolleybus' electric motor modernization by applying the bidirectional DC-DC converter and supercapacitors makes it possible to increase energy efficiency of the urban electric transport's system and to reduce the peak power demand of the supply mains. In addition, it can be used both in existing systems and in newly manufactured ones.

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