A reconfigurable structure electronic commutator for a dual BLDC motor EV drive

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Abstract. An electronic commutator that can drive a PM BLDC motor either in the full bridge or half bridge configuration has been developed. This commutator allows increasing the motor speed over the nominal value, hence the motor is able to operate within a wide constant power speed range. An application of the commutator with a reconfigurable structure for the double drive of a small electric vehicle Elipsa has been presented. The driveline consists of two independent commutators feeding the motors coupled by gears with rear wheels of the vehicle. Both commutators are controlled by a common control system based on a signal microcontroller. The results of road tests indicate new areas of BLCD motor drives application. The fact that the BLCD motor work in the second speed range does not require any changes in the motor construction and at the same time does not significantly deteriorate the drive efficiency is an indisputable advantage of the presented solution.

Key words: brushless DC motors, electronic commutator, electric vehicle (EV).

1. Introduction

Limited fossil fuel resources, especially crude oil, trigger a growing interest in the problem of electric drives in electric vehicles (EV). A solution that has been known for over a hundred years emerges again not only as a study solution but the one which is applied in the multiple production of hybrid and electric vehicles. Electric energy is a basic household and industry energy carrier and in the nearest future it will become an alternative to transport solutions [1–2].

Hybrid and electric vehicles technology development has been recently observed on many different levels. More and more efficient energy sources are being searched for. As a result, new batteries which in terms of parameters exceed the acid-lead ones have appeared on the market, also new methods of charging of batteries are developed [3]. Other energy storage systems, such as supercapacitors and fuel cells, are achieving increasingly better parameters. Methods which enable the optimization of the accumulator – motor energy flow in vehicles belong to a crucial research area. As an example we can quote new solutions known from hybrid vehicles [4–7] or attempts to use modern capacitors as energy buffers increasing the range [8–10].

For over four decades power electronics development has contributed to progress in the area of electric drives. An electronic power converter is an indispensable element, as its efficiency significantly influences the vehicle range. Much attention is paid to the reduction of conduction and switching losses. Crucial investigations are focused on both new converters as well as new or modernized solutions in high-duty electric machines.

One of the groups of electric machines which are developing especially rapidly are motors excited by permanent magnets. They are divided into brushlesss DC motors (BLDCM) and synchronous motors (PMSM) [11]. The differences between them result mainly from the construction of magnetic circuits. The way of controlling and forming the phase current is the most fundamental determinant of these machines' classification [12].

Due to their relatively simple construction, BLDC motors are applied in servodrives and small electric vehicles' drives. Aspects subjected to investigations include new constructions of these motors [13] and controlling methods which allow safety to be improved [14] as well as the optimization of motion properties. In comparison with other machines, the brushless motors have a lot of advantages:

- very high efficiency,
- linear mechanical characteristics,
- high ratio of torque per weight,
- absence of mechanical commutator and brushes.

Difficulties connected with the obtaining of operating conditions above the rated speed are an essential disadvantage of BLDC motors. It results from the fact that a typical method of extending the speed range for electric motors by reducing the excitation flux is difficult to be implemented. The main reason is the fact that the excitation flux is produced by permanent magnets and is practically constant. The area where a motor works with a speed greater than nominal and limiter power is called II zone of natural mechanical characteristics of the motor

In the case of traction drives the range of constant power work is sometimes defined as Constant Power Speed Ratio (CPSR) [4]. This factor is defined as a quotient of a vehicle's maximum speed by the speed value in which maximum torque developed by a motor is required. The factor (CPSR) varies

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for different traction drives. Extending the range of electric motor rotational speed and increasing CPSR factor involves a change of its idle run speed. For DC motors (including the brushless ones) the following relation is:

$$\omega_0 = \frac{V}{N \cdot \Phi_g} \cdot const,$$ (1)

where ω_0 value of idle speed, V – motor terminal voltage, Φ_g – motor main flux, N – the number of stator windings, *const* – construction constant.

In the case of excited DC motors, work in the II zone is obtained by reducing magnetic flux in the air-gap. With regard to the approximately constant value of permanent magnets induction, the magnetoelectrically-excited motors are not fitted for work with an increased rotational speed and reduced electromagnetic torque in the II zone. Nevertheless, investigations in this area are still being conducted.

Solutions known from literature which enable obtaining work in the II zone fall into the following categories:

a. methods based on increasing the supply voltage [15],
b. methods based on weakening the magnetic flux in motor air-gap [16],
c. methods based on changing the configuration of armature windings connection.

The application of the above methods involves using:

a. additional converters which increase the supply voltage,
b. modification of motor construction,
c. additional transistors or mechanical switches in the converter circuit.

2. Reconfigurable structure electronic commutator

One of the methods which enable the BLDC motor to obtain a speed higher than the rated value is the application of a reconfigurable structure electronic commutator. It enables a BLDC motor to work with a changed configuration of the motor main circuit connections with the converter (from full-bridge to half-bridge and inversely) – Fig. 1. The configuration change from full-bridge to half-bridge provides a possibility to double the value of voltage which feeds the motor phase windings and consequently, to increase the rotational speed. Motor work with a full-bridge converter is a standard solution. Exceeding a certain speed which approaches the idle run speed is followed by switching to a half-bridge configuration. The properties of a BLDC motor operating in the half-bridge configuration is presented in [17–18].

The configuration change from full-bridge to half-bridge provides a possibility to double the value of voltage witch feeds the motor phase windings and consequently, to increase the rotational speed. In a full-bridge structure a control system switches on/off transistors in state where supply voltage feeds two serial connected windings and in a half-bridge structure only one winding. Owing to that, it is possible to obtain two mechanical characteristics of the motor. The first one is for

the commutator operating in the full-bridge configuration and the second one for the half-bridge configuration – (Fig. 2).
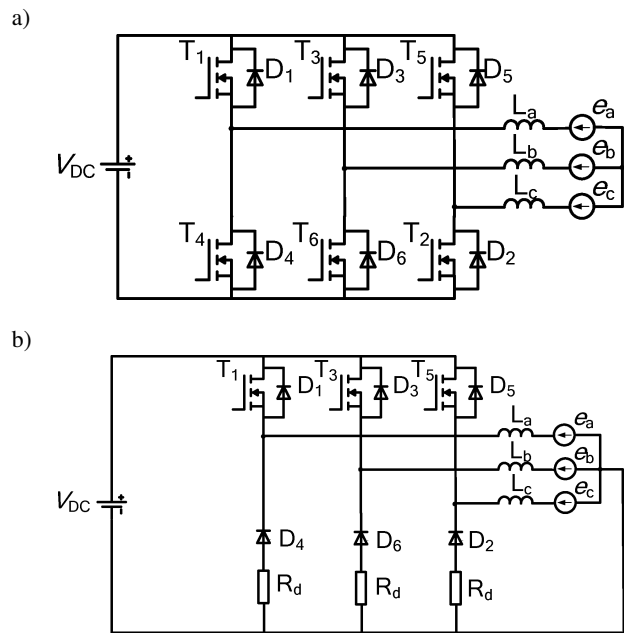
a)

b)

Fig. 1. A BLDC motor with a full-bridge (a) and a half-bridge (b) electronic commutator
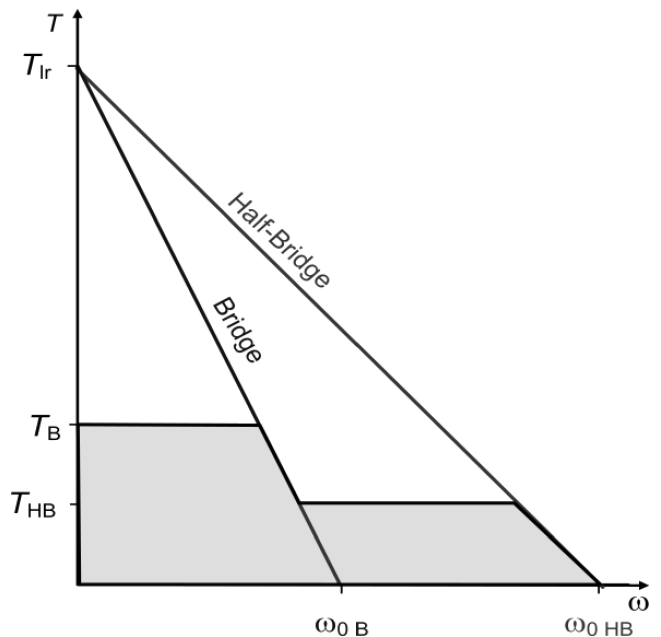

Fig. 2. The torque-speed characteristic for a PM BLDC motor drive with the bridge and half-bridge stator configuration

The mechanical characteristic of a motor can be obtained by simplified voltage relation for bridge structure:

$$V_{DC} = 2k_f\omega + 2R_s i$$ (2)

and half-bridge structure:

$$V_{DC} = k_f\omega + R_s i,$$ (3)

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where R_s value of stator phase resistance, k_f value of phase excitation factor, V_{DC} voltage applied to the motor, ω – speed value of motor, i – phase motor current.

The value of motor torque can be also described for bridge structure as:

$$T_B = 2k_f i \qquad (4)$$

and for half-bridge as:

$$T_{HB} = k_f i. \qquad (5)$$

The mechanical characteristic of a motor can be described by using voltages Eq. (2) or (3) in following relation:

$$T_B = \frac{k_f V_{DC}}{R_s} - \frac{2k_f^2}{R_s}\omega \qquad (6)$$

and

$$T_{HB} = \frac{k_f V_{DC}}{R_s} - \frac{k_f^2}{R_s}\omega. \qquad (7)$$

The stand-still torque is the same for both structures and approximates:

$$T_{lr} = \frac{V_{DC}}{R_s}k_f, \qquad (8)$$

where T_{lr} motor torque for stand-still condition.

The idle run speed for the full-bridge and half-bridge structure motor operation can be presented respectively as:

$$\omega_{0B} = \frac{V_{DC}}{2k_f} \qquad (9)$$

and

$$\omega_{0HB} = \frac{V_{DC}}{k_f}. \qquad (10)$$

A more thorough discussion on the properties of the drive has been presented in [19–21].

In order to implement both structures, a special topology of a converter with additional switches has been proposed. In Fig. 3 the BLDC motor is represented by elements of an equivalent circuit: back-EMF e_a, e_b, e_c, and stator phase inductances L_a, L_b, L_c. In the converter we can distinguish a basic structure with six transistors T_1-T_6 and additional elements: a capacitor C_0 with a diode D_0, a transistor T_H and a diode D_{H1}. The transistor T_H connects the positive terminal of the supply source with the motor windings Y-point, which makes it possible to switch to the half-bridge structure operation. Connecting the transistor T_H makes it possible to supply V_{DC} voltage to the motor phase winding with the motor current control. The additional elements are auxiliary and ensure correct operation in the half-bridge configuration. The functions of these elements are thoroughly discussed in [19]. The basic condition for this converter structure implementation is to use a 3-phase BLDC motor with Y-configurations and available star point.
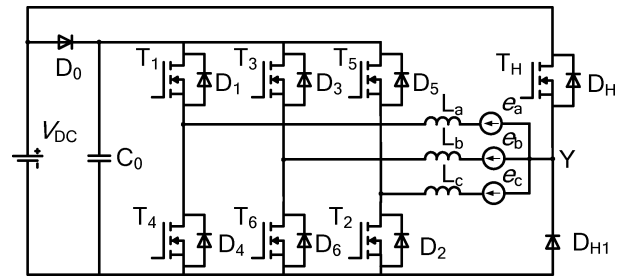

Fig. 3. A diagram of a reconfigurable structure electronic commutator

In Fig. 4 the natural characteristic $T_e = f(\omega)$ of a BLDC motor drive with a reconfigurable structure commutator, programmed by a control system, has been presented. It has been drawn with reference to the motor nominal values (torque and speed) with added characteristics of the drive output power.
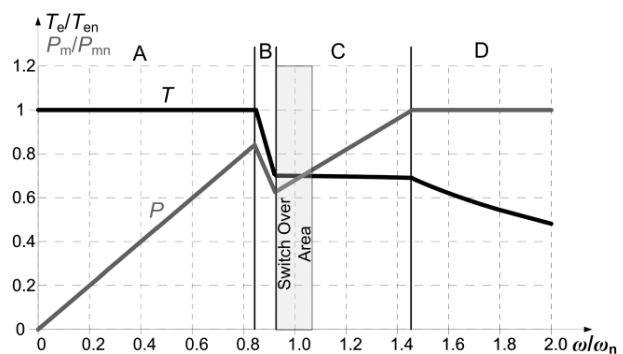

Fig. 4. Torque-speed and power-speed characteristics for a BLDC motor drive with reconfigurable structure commutator

The mechanical characteristic of the motor drive with a reconfigurable structure is composed of four fundamental sections. Sections A and B correspond with the first structure of drive named full-bridge structure motor operation. Before switching to second structure, named half-bridge structure, the control system has to reduce the torque value (section B). In practical realization control system uses hysteresis and rotational speed of switching over from full-bridge to half-bridge is greater than rotational speed for reverse switching over (switch over area – Fig. 4). This technique prevents unwanted rapid switching (chattering) between structure generated by noise (in measured speed, load torque).

Although in the half-bridge structure operations (Sec. C) the torque developed by a motor is theoretically reduced twice in relation to the full-bridge structure (at the same amplitude value of current flowing in motor windings), in the case of a change of windings current RMS value, the current value can be increased $\sqrt{2}$ time. It enables work with the torque value $T_N/\sqrt{2}$ (Sec. C), and losses in motor windings do not increase in comparison to the full bridge structure. Operation with an increased rotational speed can require the electromagnetic torque to be reduced due to the value of the motor rated power. In case of a drive with a reconfigurable structure, the necessity of operation with constant power does not follow directly the exceeding of the rated speed, but occurs within

a certain range of rotational speed (Sec. D). It results from the fact that a rotational speed increase is obtained here by changing the configuration of the converter circuit and motor connections. One can also change value of current limits, and decrease these values in half-bridge structure because of increasing iron power losses in the stator (rotational speed greater than nominal value).

3. The operation principle of a reconfigurable structure commutator

During the bridge structure operation the commutator switches are controlled in a standard method as shown in Fig. 5 [12]. The transistors T_1-T_6 are switched in cycles based on the signals coming from the rotor position sensor. At that time the transistor T_H remains turned off. The electronic commutator transistors switch supply voltage V_{DC} to the phase windings basing on the rotor Θ position angle. Another function of the transistors is to control phase currents. It is done by the master regulator that generates a PWM signal. This signal can be applied to the control signals of T_1-T_6 transistors by the logical AND operation. Not all the transisitors need to be used as motor currents' regulators. A similar effect can be obtained by controlling the current by means of only one group of transistors – positive (T_1, T_3, T_5) or negative (T_2, T_4, T_6). It reduces ripples of the motor currents. In many applications the bootstrap drivers of transistors are used. Hence, it is recommended to use a PWM signal for the positive group transistors – Fig. 5.
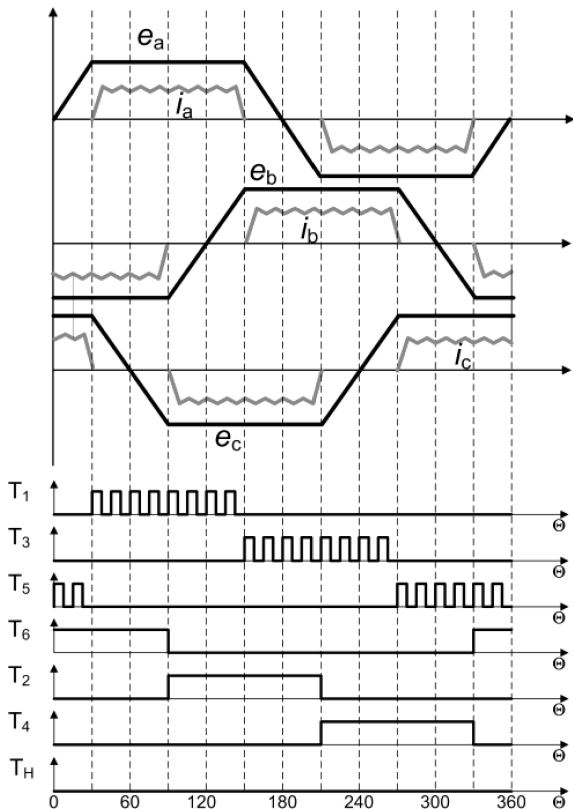
In order to switch the inverter into the half bridge structure, the transistor T_H should be turned on by the PWM signal. The same signal is used to control the positive group transistors (T_1, T_3, T_5). The way of tripping the transistors T_1-T_6 is not changed. These are presented in Fig. 6. The activated transistor T_H takes control over the motor's currents in place of the positive group transistors. The motor currents become unipolar and flow through the circuits controlled by the transistor T_H and the negative group transistors (Fig. 7a).
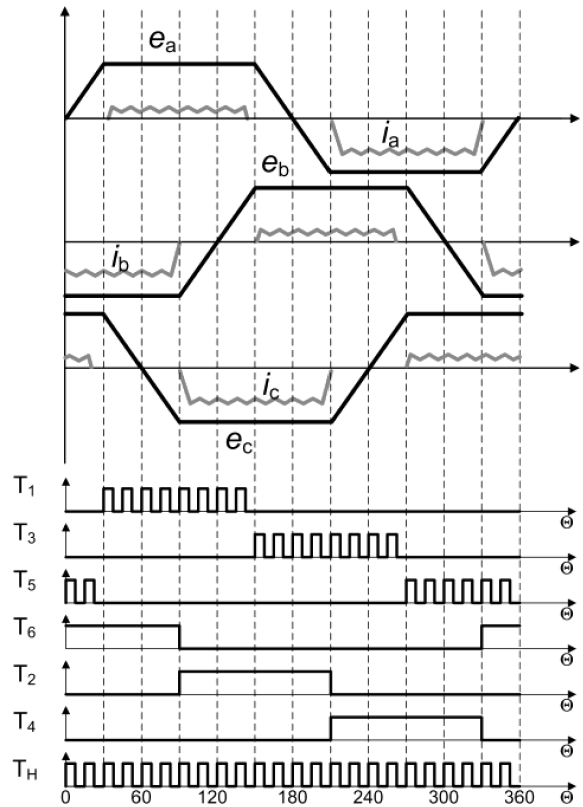

Fig. 6. Motor operation – half-bridge, back EMF, current and transistor switching signals waveforms
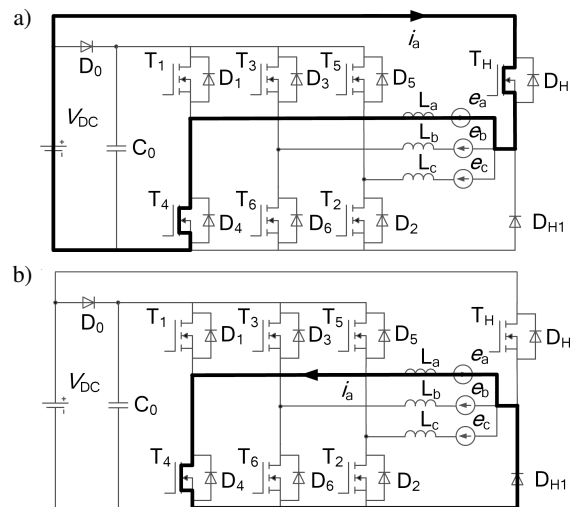

Fig. 7. Equivalent circuit of reconfigurable structure electronic commutator: a) transistors T_3, T_4, T_H are on, for $v_{C0} < V_{DC} + e_b$, b) transistor T_4 is on and T_3, T_H are off

Fig. 5. Motor operation – bridge, back EMF, current and transistor switching signals waveforms

During such work there are two commutation circuits in the system. The first one is connected with the switching off of the transistor T_H in accordance with the PWM cycle. In that cycle current flows through the circuit of diode D_{H1}, motor winding and a switched-on transistor of the negative group (Fig. 7b).

The second commutation circuit is related to the switching of the motor windings by the transistors T_2, T_4, T_6 depending on the actual value of the rotor position angle Θ. When a given transistor of the negative group is turned off, the current of the phase that is switched off drops to zero. The energy accumulated by the motor inductance is discharged in the circuit that consists of:

- if the transistor T_H is switched on (Fig. 8a) – supply voltage V_{DC}, transistor T_H, motor winding, one of the diodes (D_1, D_3, D_5) and the capacitor C_0 (Fig. 8b);
- if the transistor T_H is switched off – diode D_{H1}, motor winding, one of the diodes D_1, D_3, D_5 and the capacitor C_0 Fig. 9b).
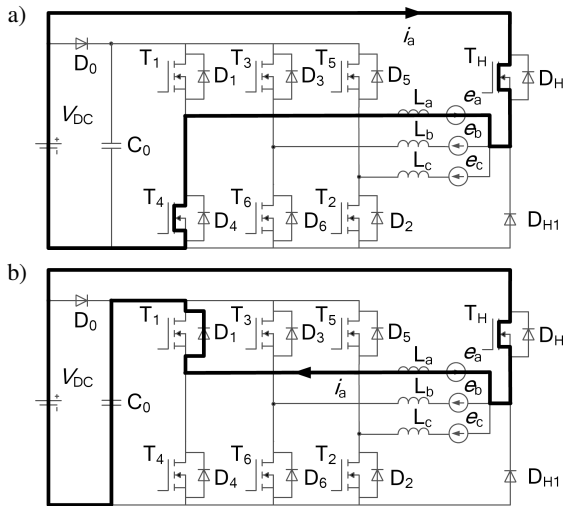

Fig. 8. Equivalent circuit of reconfigurable structure electronic commutator: a) transistors T_3, T_4, T_H are on, b) transistors T_4 is off and T_2, T_3, T_H are on

The current flow during these commutation leads to an increase in the capacitor voltage. That controlled increase of voltage has a positive effect on the operation of the drive at a rotational speed higher that nominal, when motor terminals voltage rises above some maximum value, which is approximately equal to voltage V_{DC}. In this situation an uncontrolled current flow from the motor windings to the capacitor is blocked. It would lead to a dynamic braking of the motor, disturbing the second zone of the operation as a result. It is important that the capacitor C_0 voltage increases in advance with reference to the voltage induced on the motor terminals. In order to prevent the capacitor from overloading, proper transistors of the positive group of the bridge are switched on (Fig. 6). When the capacitor voltage v_{C0} reaches the value of:
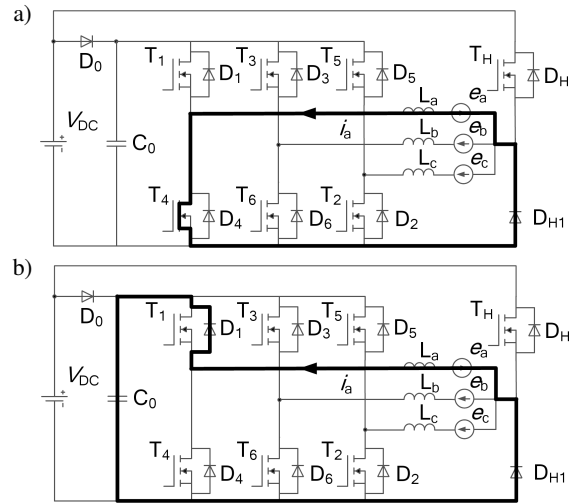
$$v_{C0} > V_{DC} + e \qquad (11)$$

Fig. 9. Equivalent circuit of reconfigurable structure electronic commutator: a) transistor T_4 is on and T_3, T_H are off, b) transistors T_4 is off and T_2, T_3, T_H are on

an additional current flows in the circuit which is marked with a dashed line in Fig. 10. This current leads to a partial discharge of the capacitor C_0 and reaches the amplitude lower than the amplitude of work current. Its value is controlled by the switching of positive group transistors, and its flow generates an additional torque developed by the motor. As a result, phase currents of the motor operating in the half-bridge structure are not quite unipolar (Fig. 6). In the phase current two components can be shown: first – the work current and second – the current connected with voltage control on the capacitor. During the drive operation the capacitor C_0 voltage can obtain a maximum value which is approximately twice as high as the supply voltage V_{DC}.
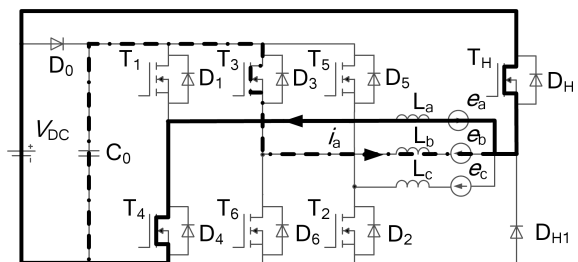

Fig. 10. Equivalent circuit of reconfigurable structure electronic commutator if transistors T_3, T_4, T_H are on, for $v_{C0} > V_{DC} + e_b$

4. Vehicle drive system

The aim of the work was to test the proposed reconfigurable structure electronic commutator in an electric vehicle. The small EV Elipsa was used as the subject of investigations. The vehicle presented in Fig. 11 was designed for 2–4 people (depending on the version) and transport load of maximum weight up to 100 kg. Two BLDC motors having a power of 2 kW drive the rear wheels through gears. The parameters of the motors are presented in Table 1.

Fig. 11. A small electric vehicle (EV) Elipsa

Table 1
Parameters of BLDC motors

P_n [kW]	V_n [V]	I_n [A]	n_n [rpm]	T_n [Nm]	I_{max}/I_n
2	48	47	2600	6	3

The drive system of EV was modified. The motors were replaced by new ones with an added neutral wire (Y-point). The new converter consisting of two reconfigurable commutators with a control system was designed and constructed. The structure of the whole drive system has been presented in Fig. 12. The BLDC motors are fed by a converter composed

of two independent electronic commutators. The battery of 48 V nominal voltage and 225 Ah capacity serves as a source of energy. Both commutators are controlled by a common system based on DSP TMS 320F2812. An additional CPLD Lattice ispMACH 4A series has been used to form control signals of transistors. Control functions are based on the position of the rotor and the additional 4 signals from DSP which define the state of the drive system (stop/start, back/forward, motor/brake, full-bridge/half-bridge).

The rotor's position is indicated by Hall-effect position sensors (RPS) located in the motors. Transistors are driven by specialized integrated circuits IR 2130. The electronic commutators are based on MOSFET transistors IRFS 4310, two connected in parallel, so as to increase the maximum current value to 150 A per branch. The power circuits of the converter were made in printed circuit technology ThermalClad using SMD assembly. In order to reduce the voltage drop across diode D_0 terminals, the Schottky diode type 111CNQ045A has been used. An integral diode of the MOSFET transistor which was permanently switched off serves as the diode D_{H1}. The capacitors C_0 of both commutators are installed outside the main board. The rewrite above the main circuits of the converter are presented in Fig. 13. The power circuits board is connected to a control board with IR2130 drivers, LEM current sensors and circuits that couple the analogue and digital part with the microcontroller.
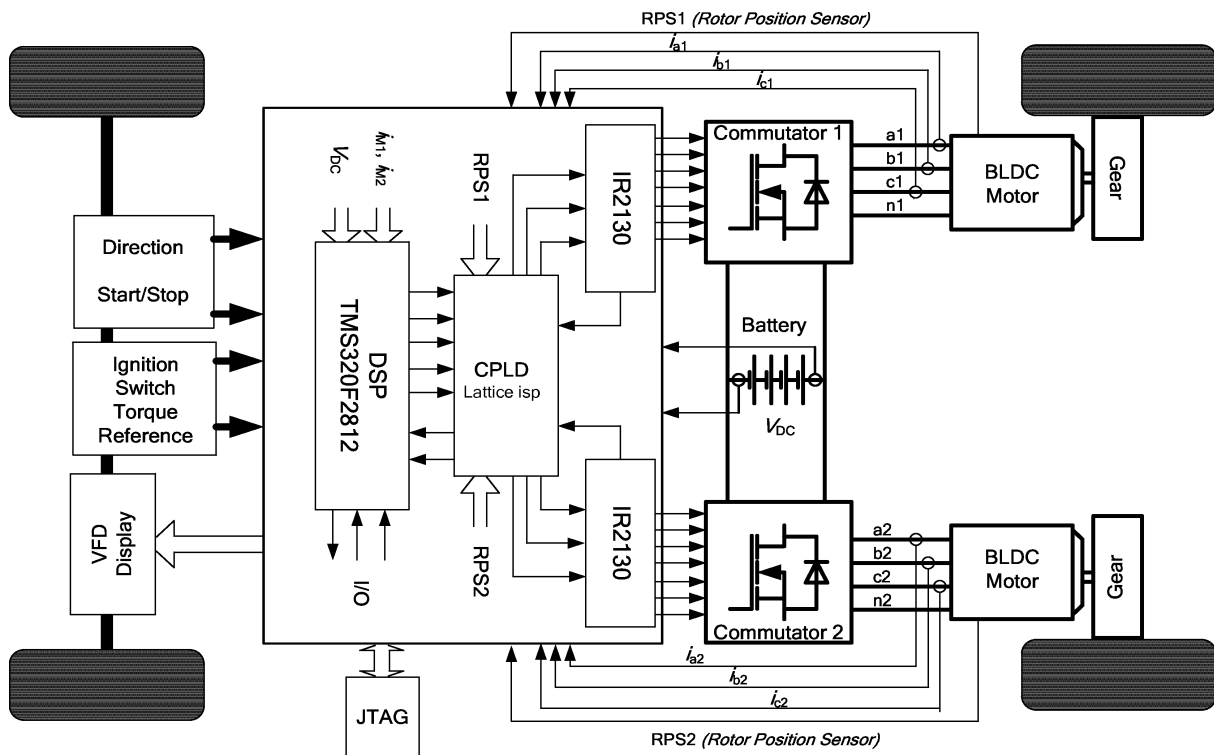

Fig. 12. The EV drive system with two reconfigurable structure electronic commutators
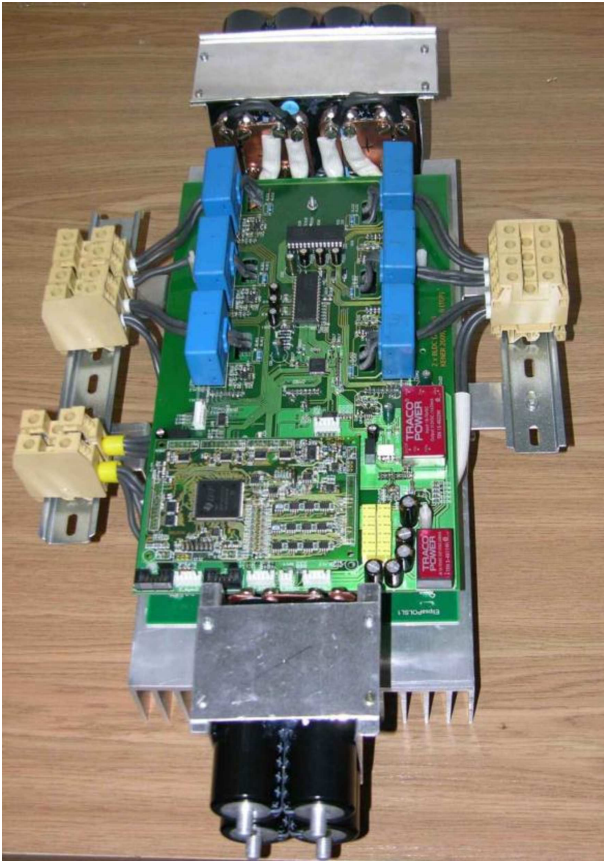
Fig. 13. A prototype of the converter based on two reconfigurable structure electronic commutators

The control system is based on a digital signal microcontroller (DSC) TMS 320F2812, a block diagram of which is presented in Fig. 14. The EV driver can choose a run direction (forward, backward, stop) and can set a torque value by means of an acceleration pedal. Basic parameters are presented on a VFD display: direction, speed, battery condition. A basic assumption has been made that the EV steering should be similar to that of a typical vehicle with a combustion engine. In this way an average user should not have problems with operating the vehicle. For this reason the value set from the acceleration is the reference torque value. The run direction is set by means of an additional switch. The maximal value of acceleration is limited by the ramp block. The reference torque (current) value is formed not only by the accelerator pedal but also by the state controller block, which significantly modifies the ramp block and the current controller operation, as shown in Fig. 14.

The state controller block also works out signals to the CPLD which determine the way of the formation of impulses that control the converter transistors, including the switching points of commutator structures (bridge/half-bridge). The PWM signal having a constant frequency of 12 kHz results from a PI current (torque) controller work. The commutator overcurrent protection is based on the additional function of IR2130 drivers, which generate fault signals that stop the device operation. It is also used with other fault signals by a vehicle diagnostic system, which saves the events in non-volatile memory and visualizes relevant information to the EV driver [22].
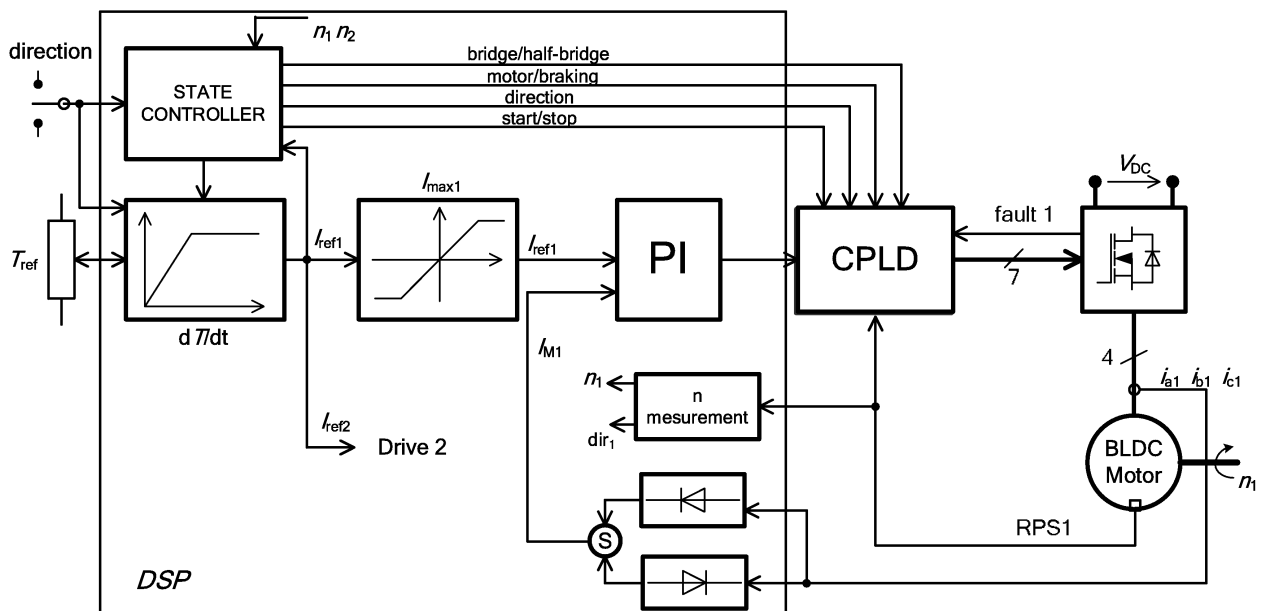

Fig. 14. A schematic diagram of the control system of the drive with reconfigurable structure electronic commutator

5. Laboratory and road tests of the EV drive

A converter which was constructed and subjected to laboratory tests, was installed in an electric vehicle Elipsa. In the earlier solution with a classic commutator with BLDC motors and mechanical 10:1 ratio gears which drive an 18-inch diameter wheel, the EV reaches the maximum speed of 25 km/h.

The converter was replaced by a new one with reconfigurable structure electronic commutators presented in chapter 4. First laboratory tests were done with one commutator and BLDC motor. The second part of the test was carried out with EV. During the driving tests selected measurements were recorded. The performed experiments confirm the correct operation of the drive system while starting, switching to the half-bridge structure and during recovery braking.

Figure 15 presents the start of a vehicle from 0 to the final speed 4000 rpm for BLDC motors. The current waveforms for both motors (i_s^{M1}, i_s^{M2}) are similar. In the first part, in the full-bridge structure (for motor rotational speed ranging from 0 to 2400 rpm) the current is bipolar. Its amplitude is constant up to the point in which it becomes gradually reduced before switching over to the half-bridge structure (above the speed of 2400 rpm). At that time the capacitor C_0 voltage behaves like supply battery voltage – due to the consumption of an increasing amount of power during the acceleration, the voltage gradually drops. At the moment of switching over to the half-bridge structure a characteristic quasi-step increase of the voltage value on the capacitor C_0 (v_{C0}^{M1} in Fig. 15) takes place. Afterwards, the voltage increases proportionally to the motor rotational speed value, and the current is quasi-unipolar.
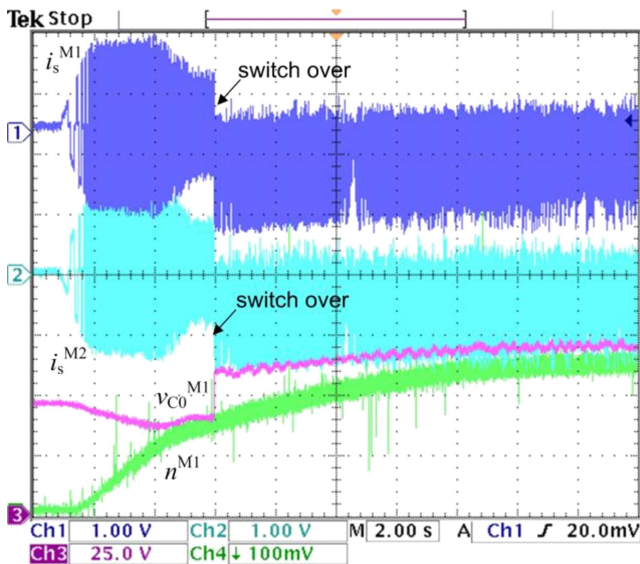

Fig. 15. Waveforms of motor phase currents: i_s^{M1}, i_s^{M2}, voltage on capacitor v_{C0}^{M1} and motor rotational speed of motor no 1 n^{M1}, during the start-up to the speed of 35 km/h; current scale 100 A/div, voltage scale 25 V/div, motor speed scale 250 mV $- > 4000$ rpm, time scale 2 s/div

Figure 16, showing zoomed-in the switching over process, indicates that the moment of changing the structure of both commutators does not have to be simultaneous. It results from the possibility of obtaining different rotational speeds by particular motors, for example while driving on a curve. The motor speed values provide a basis for the control system to force the switching over process. Such a condition is completely normal and does not have any influence on the traction properties of the vehicle. Neither is it sensed in any way by the EV driver.
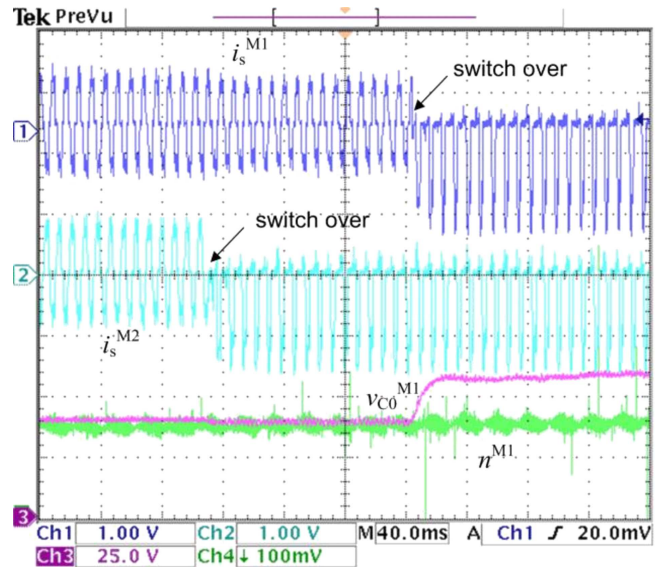

Fig. 16. Waveforms of motor phase currents: i_s^{M1}, i_s^{M2}, voltage on capacitor v_{C0}^{M1} and motor rotational speed of motor no 1 n^{M1}, during the switching over of the commutators' structure; current scale 100 A/div, voltage scale 25 V/div, motor speed scale 250 mV $- > 4000$ rpm, time scale 40 ms/div

As far as the voltage class of capacitors and transistors is concerned, a maximum permissible voltage level on capacitors C_0 has been accepted as 85.5 V. It allowed acquiring a maximum EV speed of 37 km/h when driving on a flat road. In order not to exceed these parameters while driving downhill, the control system additionally realized the maximum speed controller P-type with a setpoint of motor speed reaching 4500 rpm.

Figure 17 illustrates the drive system braking process. Switching to braking is forced after a driver releases the acceleration pedal. The set current is reduced to zero and next the system is switched over by the state controller to the braking operation. The proper value of the set current (braking torque) gives an impression of control over the vehicle, like motor braking in a combustion engine vehicle. In the Fig. 17 one can notice asymmetrical waveforms of the motor phase currents and a steadily decreasing speed of one of them.

It is worth noticing that the process of discharging the commutator capacitors is smooth. It results from the fact that during the braking operation the energy is transmitted from the rotating motor to the capacitor and next from the capacitor to the battery.
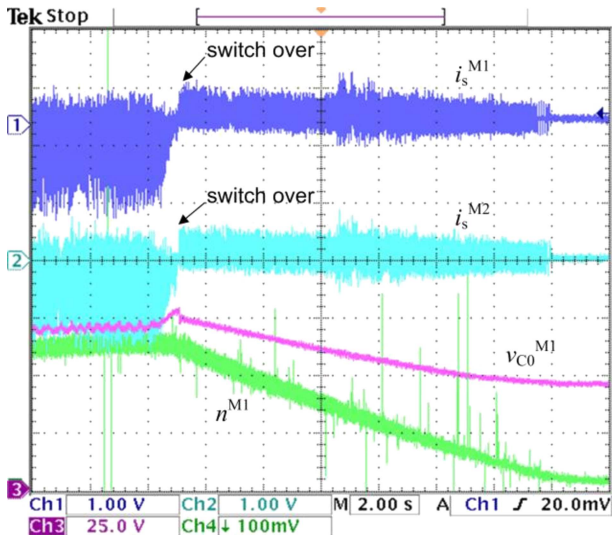
Fig. 17. Waveforms of motor phase currents: i_s^{M1}, i_s^{M2}, voltage on capacitor v_{C0}^{M1} and motor rotational speed of motor no1 n^{M1}, while EV is decelerates from speed 35 km/h to 0; current scale 100 A/dz, voltage scale 25 V/dz, motor speed scale 250 mV->4000 rpm, time scale 2 s/div

Figure 18 presents a measured mechanical and electrical value of EV registered during one of the test trips. At that time the vehicle was moving along the test route at different speeds, it accelerated and braked – altogether it covered a distance of 18 km. In the measurements of the power flow from the battery (Fig. 18b) one can notice moments of recovery braking when the energy is returned to the source. The ratio of power returned to the battery to the power drawn from battery during the test trip indicates that only a slight amount of energy can be recovered in that way. A definitely larger value could be obtained by an additional coupling of the mechanical brake pedal with the control system and increasing the value of the braking current depending on its location. However, it requires allowing a considerable amount of current to instantaneously return to the battery.

In the final part of the test trip a voltage decrease on the battery is noticeable (also maximal value of power – Fig. 18b). As a result, the control system limited the power drawn from the source in order to protect the battery from an excessive deep discharge. One can notice a gradually decreasing current amplitude of motor M1 presented in Fig. 18c. The same situation is observed in the case of motor M2.

The tested electric vehicle covered the distance of about 500 km. During the tests an optimal traction characteristic of the drive was verified and finally established. A maximum linear speed of the vehicle was obtained – 37 km/h. It gives a 50% increase of a vehicle speed range in comparison to the earlier solution, although the parameters of BLDC motors were unchanged.

The tests with the new converter revealed a 30% drop of a vehicle range compared to the standard solution with a classic electronic commutator (and a maximum speed of 25 km/h). It results from an increase of power drawn from the battery, which is caused by a growth in the vehicle movement resis-

tance to a higher average speed of the trips. The resistance includes the air resistance as well as the resistance resulting from mechanical gears and tires applied in the vehicle. An additional factor affecting a decrease in the vehicle range is the fact that the drive efficiency in the half-bridge structure is 10% lower than in the full-bridge one. Increased iron losses, resulting from a higher magnetic field frequency, contribute to a reduced efficiency of the drive in the half-bridge structure. Other factors which determine the drive efficiency include phenomena connected with commutation processes in the converter. Commutation in the converter circuits in the half-bridge structure proceeds in definitely more difficult conditions than in the full-bridge one. Motor phase currents during commutation in the half-bridge structure in each operation cycle are reduced to zero. In the full-bridge structure, however, commutation always proceeds in three motor phases.
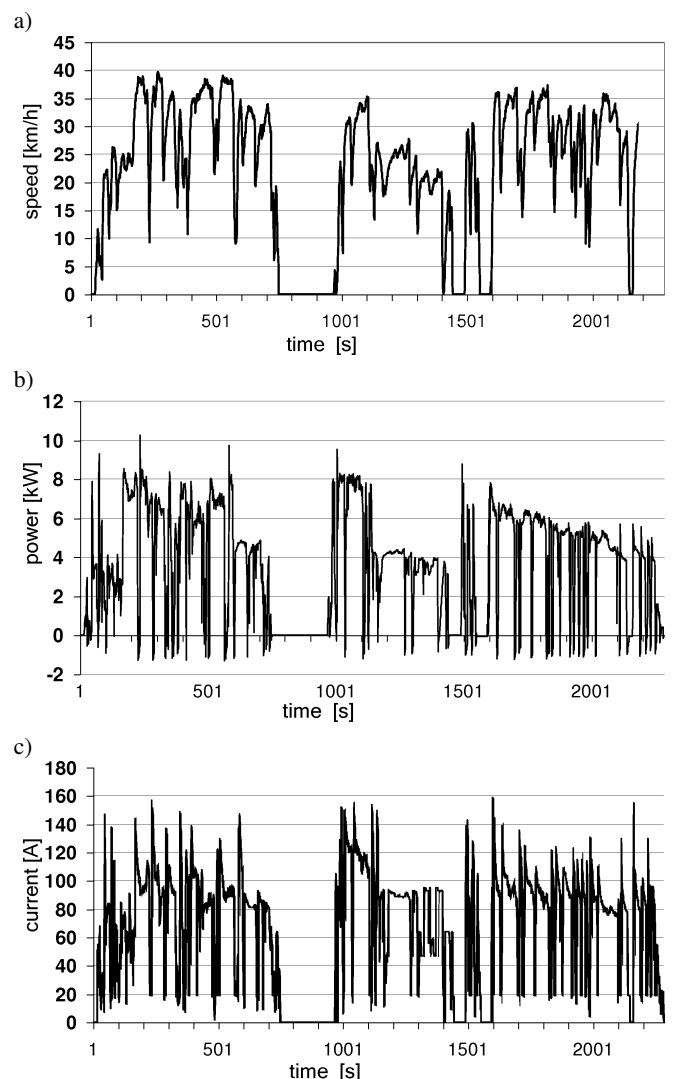

Fig. 18. A measurements from the EV test trip: a) EV speed, b) power drawn form the battery, c) BLDC motor M1 current

It should be noted that the received parameters of the vehicle: starting torque, maximum speed, acceleration and range are accepted by the vehicle producer.

6. Summary

The article presents the results of research on the application of the drive system of a small electric vehicle with brushless DC motors. The application of reconfigurable structure commutators made it possible to increase the maximum speed of the vehicle by 50%, without changing the motor parameters. Moreover, it has been proved that in a brushless DC motor drive there is a possibility of obtaining a traction characteristic which is similar to that obtained in drives with shunt DC motors or induction motors.

The proposed system also enables braking with energy return to the battery. The results obtained during the project works indicate new areas of the BLDC motor drives application. An indisputable advantage of the developed solution is the fact that the BLDC motor work in the second speed zone does not require any changes in the motor construction and at the same time the drive efficiency is not significantly worse.

REFERENCES

[1] M. Ehsani, Y. Gao, S.E. Gay, and A. Emandi, *Modern Electric Hybrid Electric, and Fuel Cell Vehicles – Fundamentals, Theory, and Design*, CRC Press, London, 2005.

[2] P. Droege, *Urban Energy Transition – from Fossil Fuels to Renewable Power*, Elsevier, Amsterdam, 2008.

[3] R.M. Miskiewicz and A.J. Moradewicz, "Contactless power interface for plug-in electric vehicles in V2G systems", *Bull. Pol. Ac.: Tech.* 59 (4), 561–567 (2011).

[4] N.P. Shah, A.D. Hirzel, and Cho Baekhyun, "Transmissionless selectively aligned surface-permanent-magnet BLDC motor in hybrid electric vehicles", *IEEE Trans. Ind. Electron.* 57 (2), 669–677 (2010).

[5] A. Emadi, L. Young Joo, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles", *IEEE Trans. Ind. Electron.* 55 (6), 2237–2245 (2008).

[6] C.H. Chen and M.Y. Cheng, "Implementation of a high reliable hybrid electric scooter drive", *IEEE Trans. Ind. Electron* 54 (5), 2462–2472 (2007).

[7] K.T. Chau, C.C. Chan, and L. Chunhua, "Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles", *IEEE Trans. Ind. Electron* 55 (6), 2246–2257 (2008).

[8] I. Aharon and A. Kuperman, "Topological overview of power-trains for battery-powered vehicles with range extenders", *IEEE Trans. Pow. Electron.* 26 (3), 868–876 (2011).

[9] A. Hammar, P. Venet, R. Lallemand, G. Coquery, and G. Rojat, "Study of accelerated aging of supercapacitors for transport applications", *IEEE Trans. Ind. Electron.* 57 (12), 3972–3979 (2010).

[10] A. Affanni, A. Bellini, G. Franceschini, P. Guglielmi, and C. Tassoni, "Battery choice and management for new-generation electric vehicles", *IEEE Trans. Ind. Electron* 52 (5), 1343–1349 (2005).

[11] M. Janaszek, "New method of direct reactive energy and torque control for permanent magnet synchronous motor", *Bull. Pol. Ac.: Tech.* 54 (3), 299–305 (2006).

[12] R. Krishnan, *Electric Motor Drives. Modeling, Analysis, and Control*, Prentice Hall, London, 2001.

[13] Hak-In Lee and M.D. Noh, "Optimal design of radial-flux toroidally wound brushless DC machines", *IEEE Trans. Ind. Electron* 58 (2), 444–449 (2011).

[14] S. Dwari and L. Parsa, "Fault-tolerant control of five-phase permanent magnet motors with trapezoidal back EMF", *IEEE Trans. Ind. Electron.* 58 (2), 476–485 (2011).

[15] P. Bajec, D. Voncina, D. Miljavec, and J. Nastran, "Bi-directional power converter for wide speed range integrated starter-generator", *Proc. IEEE Int. Symp. on Industrial Electronics ISIE 2004* 2, 1117–1122 (2004).

[16] J.S. Lawler, J.M. Bailey, J.W. McKeever, and J.O.P. Pinto, "Extending the constant power speed range of the brushless dc motor through dual-mode inverter control", *IEEE Trans. Power Electron.* 19 (3), 783–793, (2004).

[17] R. Krishnan, "A novel single-switch-per-phase converter topology for four-quadrant PM brushless DC motor drive", *IEEE Tran. Ind. Appl.* 33 (5), 1154–1161 (1997).

[18] R. Krishnan and S. Lee, "PM brushless DC motor drive with a new power-converter topology", *IEEE Tran. Ind. Appl.* 33 (4), 973–982 (1997).

[19] K. Krykowski and A. Bodora, "Properties of the electronic commutator designed for two zone operation of PM BLDC motor drive", *Proc. IEEE Int. Symposium on Industrial Electronics ISIE 2005* 1, 177–182 (2005).

[20] K. Krykowski and A. Bodora, "Variable structure bridge/half-bridge electronic commutator for PM BLDC motor supply", *Proc. IEEE Int. Symposium on Industrial Electronics ISIE 2005* 3, 905–910 (2005).

[21] K. Krykowski and A. Bodora, "Efficiency and power losses in PM BLDC motor with variable bridge/half-bridge structure electronic commutator", *Proc. Power Electronics and Motion Control Conf. PEMC 2008* 1, 326–330 (2008).

[22] A. Bodora, T. Biskup, and A. Domoracki, "Two zone drive of small EV based on BLDC motors", *Electrotechnical News* 78 (12), 42–47, (2010), (in Polish).