UNCONNECTED WINDING TORQUE RIPPLE REDUCTION IN BLDC MOTORS USING A PWM TECHNIQUE

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Abstract— **A modulation method for BLDC motors with unconnected windings is presented in this article. Two complete bridges are used in this process (or three 12-switch H-bridges). The defined modulation allows for a reduction in the motor current variable while increasing the motor current ripple frequency (fourfold in relation to the switching frequency). The most significant advantage of a 12-switch inverter is the twofold reduction in dc-link voltage while preserving rated rpm (voltage reduction in comparison to a typical supply method). Losses on semi-conductor elements are reduced as the voltage is reduced. The proposed modulation technique also greatly reduces the time of current commutation between windings, according to the paper.**

Keywords- BLDC motor, open-end winding, PWM technique, unipolar modulation

I. INTRODUCTION

In recent years, due to the developments in power electronics and therefore the availability of cheap semiconductor components, numerous research centers started work on stepper, induction and reluctance brushless motors [1] or PMSM static magnet motors and BLDC motors [2–4]. Because of easy control methods and high power density, this last type has found variety of applications in various sectors of industry: automotive [5, 6], automation, etc. albeit BLDC motors are known for years, there are still numerous research projects getting to improve their performance.

One of the most areas of the research are sensor less methods [5–9] supported back voltage (BEMF) measurements during a non-energized winding, also as modifications to pulse width modulation (PWM) allowing the detection of the rotor position at start-up (BEMF near zero). Additional impulses causing current flow in subsequent windings are interwoven into the PWM cycles [9, 10]. Supported observations of the speed at which the present increases, the inductivity of the circuit is decided, thus showing the position of the rotor relative to the stator. Compared to the quality modulation, extra pulses are shorter by not bringing significant moments of parasitic and don't affect the motor.

Another important aspect of research on BLDC motors is that the Commutation Torque Ripple thanks to the loss of control over the present during current switching between consecutive windings, also because the non-zero inductance of the winding that starts the conduction, which limits the speed of current increase.

One concept meant to attenuate the torque ripple during commutation involves special modulation techniques that allow the simultaneous flow of current through all the motor windings [3, 11–13].

Motor braking requires the receipt of energy from the rotating mass of the rotor and dampening it within the resistors, transferring it to the energy storage or returning it to the availability network [14–16]. The phenomenon of energy storage during a rotating mass are often wont to improve the standard of electricity [17].

An important research area is said to methods of rotational speed regulation. The change of the rotational speed is performed by changing the typical the worth of voltage applied to motor windings. The subsequent techniques are often used for this purpose: Pulse Width Modulation (PWM) [8, 10], Pulse AM (PAM) [8, 10], and Hysteresis current control [1].

The primary of the mentioned methods requires maintaining a continuing voltage at the dc-link capacitor, and therefore the regulation of the voltage at motor terminals is performed by changing the duty cycle of power inverter pulses. Within the PAM method, the voltage at the dc-link capacitor is subject to regulation (depending on rotational speed), and therefore the power inverter transistors are conducting current for $2/3\pi$ (their switching frequency results from rotational speed). The capacitor voltage are often regulated using e.g. a thyristor rectifier [8]. Analyzing the properties of both methods, it are often concluded that PWM power inverters are used for low-speed motors, while PAM power inverters are better fitted to devices with motors of high rotational speed [8].

A BLDC motor can include delta winding connections powered from six transistor inverters [18–22]. In such a connection, current always flows through three windings (in a delta winding connection, the present flows through two phases). When maintaining a continuing electromagnetic moment, this causes the phase currents and ripples to possess higher values during a delta connection than during a star connection. Within the presented solution the ripples are reduced, the dc-link voltage is reduced twofold and therefore the dc-link current frequency is increased four fold. Halving the dc-link voltage reduces the losses during transistor switching operations (in comparison to classic BLDC motor supply methods [20–24]).

II. OPEN-END WINDING PWM TECHNIQUE

Typically, three-phase BLDC motors are connected in star configuration, even if the beginnings and ends of windings are available. Due to the method of feeding, motors of this type cannot be connected in delta configuration [11–20].

The BEMF of a BLDC motor is described by the relationship:

$$e = k.w_r \qquad (1)$$

Where: e is the motor BEMF voltage, k is the excitation coefficient, ω is the rotor angular speed

When motor windings are connected in star configuration, the instantaneous voltage at a single winding is equal to half of the DC link voltage. This means that the DC link voltage must be at least twice as high as implied by Equation (1) in order to achieve the required rotational speed. A surplus of the DC link voltage above the BEMF is required in order to force a current flow in the windings. In the case of open-end winding motors it is possible to supply a motor by two bridge power inverters connected respectively to the beginnings and ends of windings (Fig. 1).
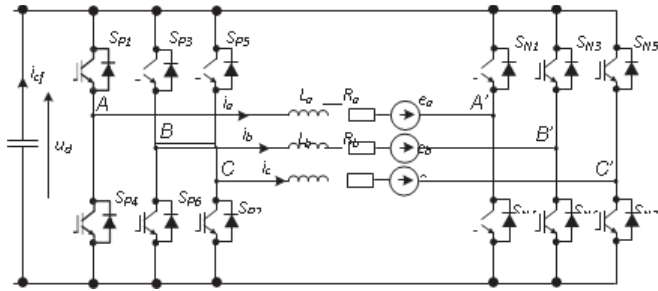

Fig. 1. Open-end winding BLDC motor power supply scheme

The DC link voltage (ud) is connected directly to every winding, therefore a voltage not lower than the BEMF is sufficient for achieving the required speed. This means that the DC link voltage of the system from Fig. 1, necessary for achieving the required speed, is approx. two times lower than for a system with the winding connected in star configuration. Therefore, the system from Fig. 1 can be realized using less expensive elements, transistors of lower permissible EC voltage, less expensive transistor drivers, and capacitors of lower operating voltage. The ability to use less expensive elements compensates for the need to use an additional semiconductor bridge. Moreover, each of the windings is supplied from a separate power inverter branch, therefore there is no problem with current switching between windings when the rotor passes the switching points. A lower voltage at the dc-link capacitor results also in lower losses at semiconductor elements.

With windings connected as in Fig. 1 it is possible to use unipolar modulation analogous to the modulation used in one-phase systems, which makes it possible to obtain a frequency of the ac component of the current that is two times higher than the transistor switching frequency. This part of the proposed solution makes it possible to use motor chokes (low-pass filters) of inductance that is two times lower than in the conventional solution, while keeping the same value of the ac component of the current. The idea of this modulation is presented in Fig. 2. If the instantaneous value of the signal u_{ref} is positive and greater than that of the saw-tooth waveform, the upper transistor of the branch SP1 is switched on, which makes the potential of the beginning of the winding equal to the potential of the positive electrode of the dc-link capacitor. From this it follows that the voltage at the beginning of the winding (point A) measured with relation to point M (Fig. 3) is equal to the power supply voltage Ud. The torque in a BLDC motor is proportional to the current, therefore the torque pulsation of a motor supplied in the described way is characterized by a very high frequency, four times higher than the switching frequency and a relatively low value of pulsation.
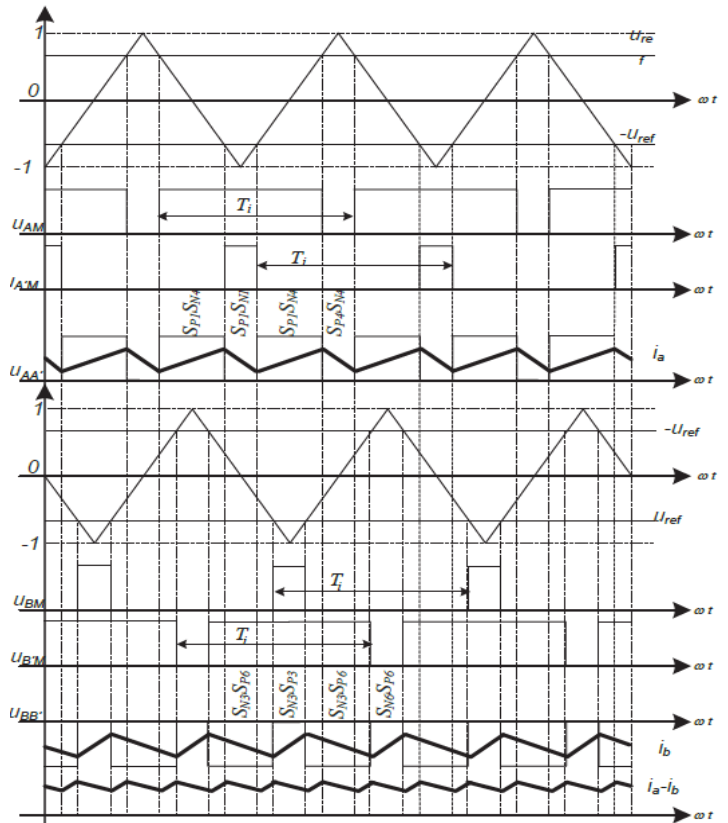

(a)
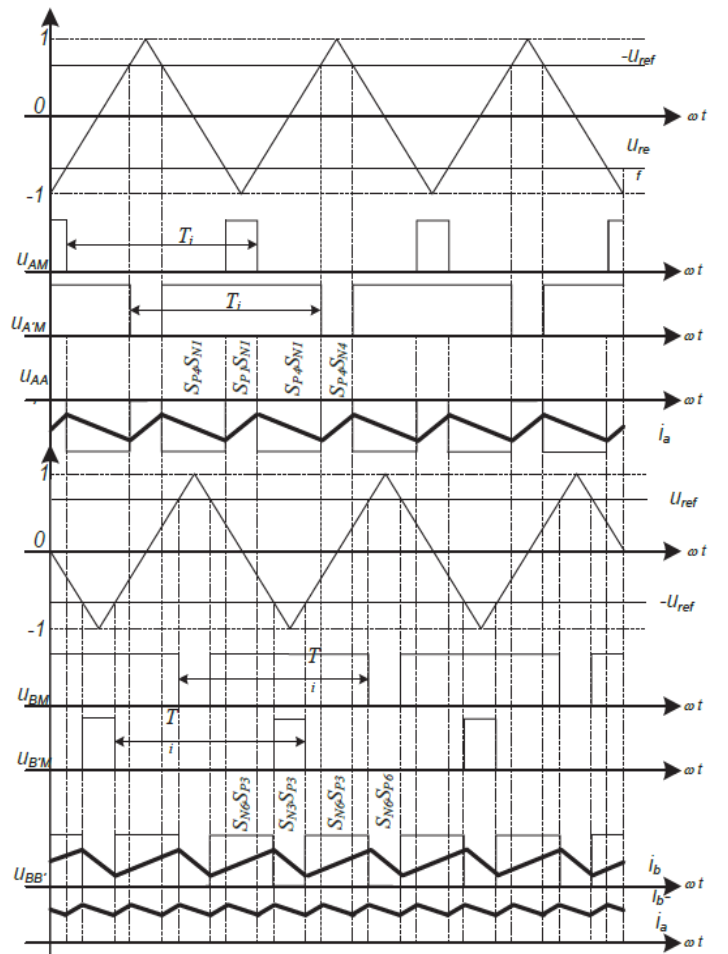
(b)

Fig. 2. Method for generating the PWM signal for current flow: (a) from point A to AJ and from BJ to B; (b) from point AJ to A and from B to BJ

The four times greater value of the frequency of the ac component with relation to the transistor switching frequency is obtained thanks to the phase shift of the saw-tooth waveforms in the PWM signal generator.

As shown in Fig. 2, one period of transistor operation consists of four stages resulting from the conducting semiconductor elements. All operating states and the path of current flow in the circuit are presented in Fig. 4. The current flow path has been marked in black, and the elements which do not take part in the current flow are marked in grey.

A precise analysis of the operating states of transistors during one switching cycle reveals that the period consists of four stages, however, the first and third stage are identical. In the first stage of the cycle (Fig. 4(a)) current flows through transistors SP1 and SN4 and it is forced by the difference between the dc-link voltage Ud and the BEMF of phase a (ea). After switching off the transistor SN4 and applying a gating impulse to transistor SN1, under the influence of the energy accumulated in the inductance of the windings and the BEMF, current flows through the diode of transistor SN1, transistor SN1 is not conducting current, Fig. 4(b).

In this state there is no exchange of energy between the dc-link capacitor and the motor. The following stage of modulation is identical with the first one, current flows through transistors SP1 and SN4. In the last stage of modulation, after opening transistor SP1 and driving transistor SP4, current flows through transistor SN4 and the diode antiparallel to transistor SP4. Like in the case indicated in Fig. 4(b), current flows under the influence of energy accumulated in the magnetic field of the inductance of the windings and the BEMF. In a BLDC motor, current flows through two windings simultaneously, however, Fig. 4 presents the current path for one of the phases only, because a similar analysis can be performed for the remaining windings.

Fig. 3. Marking of the voltages for one phase of the motor

(a)
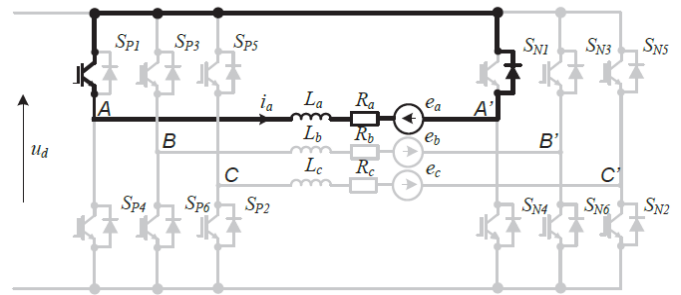
(b)
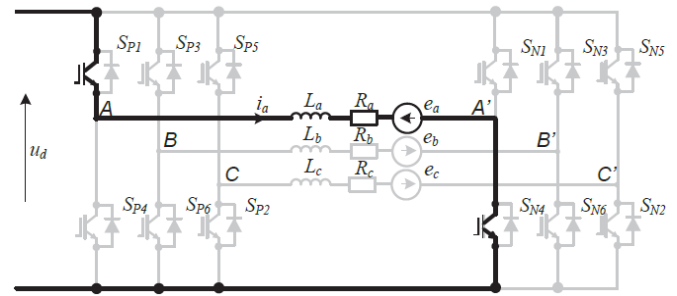
(c)
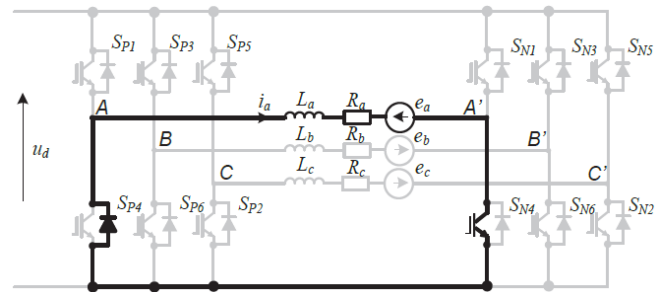
(d)

Fig. 4. Path of current flow during one switching period
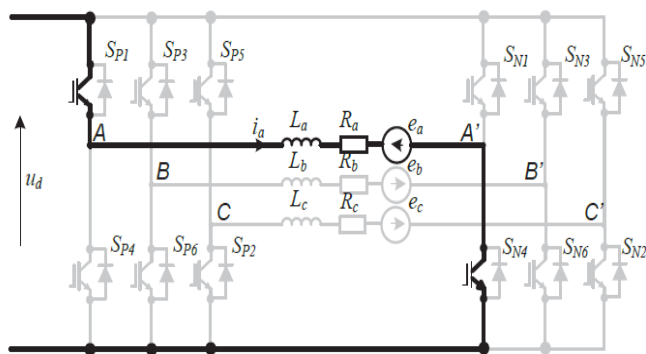
III. PWM GENERATOR

At any given time, current in three-phase BLDC motors flows through two windings, and the third one remains unpowered. Therefore, there are three different combinations of conducting phases. Taking into account the directions of current flow through the windings, a total of six different operational states of the windings can be obtained. As it results from Fig. 2, the saw-tooth waveforms of the PWM generator for the conducting phases are shifted with respect to each other by n/2. In order to ensure proper modulation for all combinations of conducting phases, it is necessary to generate two saw-tooth waveforms shifted with respect to each other, and to use them sequentially, in accordance with the sequence of powered phases that results from the direction of the motor rotation. Fig. 5 presents an example of an assignment of the carrier waveforms (carrier A, and carrier B shifted by $\pi/2$) to the conducting phases.

In order to illustrate better the assignment of the carrier waveforms to the powered windings, signals from the sensors of rotor position (HA, HB, HC) and BEMF (eA, eB, eC) have also been included in Fig 5.
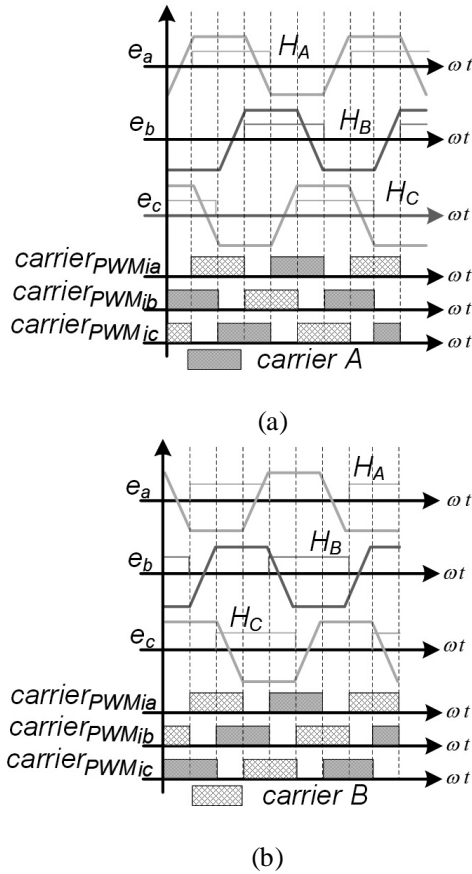

(a)

(b)

Fig. 5. Assignment of the carrier waveforms to the conducting phases

As it results from Fig. 5, the assignment can be made on the basis of signals from the rotor position sensor. Moreover, in the combination proposed in Fig. 5 the direction of rotation does not affect the assignment of the carrier waveforms to the respective phases.

The following assignment functions can be assumed on the basis of Fig. 5:

$$carrier_{\text{PWM}_{ia}} = \begin{cases} carrier_B & \text{if } \left(H_A \wedge \overline{H_B}\right) \\ carrier_A & \text{if } \left(H_B \wedge \overline{H_A}\right) \end{cases}$$

$$carrier_{\text{PWM}_{ib}} = \begin{cases} carrier_B & \text{if } \left(H_B \wedge \overline{H_C}\right) \\ carrier_A & \text{if } \left(H_C \wedge \overline{H_B}\right) \end{cases},$$

$$carrier_{\text{PWM}_{ic}} = \begin{cases} carrier_B & \text{if } \left(H_C \wedge \overline{H_A}\right) \\ carrier_A & \text{if } \left(H_A \wedge \overline{H_C}\right) \end{cases}$$

(2)

Where: carrier PWM ia is the saw-tooth (carrier) waveform used by the PWM generator for motor

Phase b, carrier PWM ib is the saw-tooth (carrier) waveform used by the PWM generator for motor

Phase c, carrier PWM ic is the saw-tooth (carrier) waveform used by the PWM generator for motor phase c.

IV. SWITCHING LOGIC

Information about the position of the rotor with respect to the windings is necessary in order to properly supply a BLDC motor. Determination of the rotor position with respect to the stator is realized using Hall sensors or sensorless methods. The control system supplies adequate windings with power on the basis of the rotor position information. Waveforms of BEMF, signals from the sensors of rotor position (HA, HB, HC), and transistor control pulses are presented in Fig. 6. The figure has been prepared for motoring operation and for both directions of rotation.
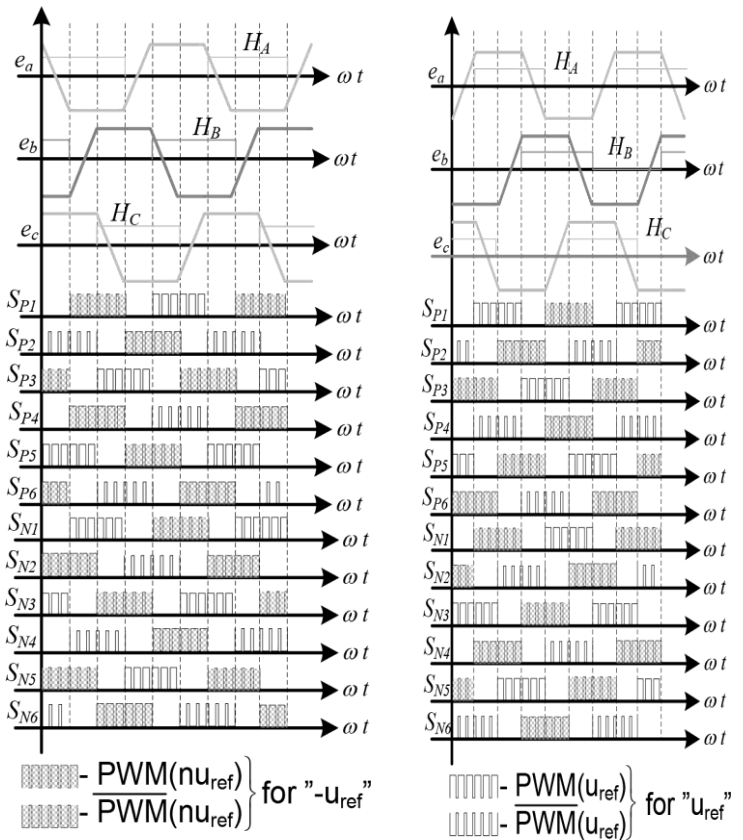

Fig. 6. Waveforms of BEMF, rotor position signals, and transistor control pulses for both directions of rotation: (a) clockwise CW and (b) counterclockwise CCW.

Logic functions for easy implementation of control have been determined on the basis of Fig. 6. Two waveforms have been used for transistor control: PWMuref obtained from comparing the saw-tooth waveform with the reference signal u ref, and PWMnu ref which uses the signal uref for comparison.

The control functions for both directions only differ in the method of assigning the signals PWMu ref and PWMnu ref. After introducing the relationship:

$$PWM_1 = \begin{cases} PWM_{u\,\text{ref}} & \text{if } CW \\ PWM_{nu\,\text{ref}} & \text{if } CCW \end{cases}$$

$$PWM_2 = \begin{cases} PWM_{nu\,\text{ref}} & \text{if } CW \\ PWM_{u\,\text{ref}} & \text{if } CCW \end{cases}$$

(3)

Finally the switching logic functions:

$$S_{P1} = \left(H_A \wedge \overline{H}_B \wedge \mathrm{PWM}_1\right) \vee \left(\overline{H}_A \wedge H_B \wedge \mathrm{PWM}_2\right)$$
$$S_{P2} = \left(H_C \wedge \overline{H}_A \wedge \mathrm{PWM}_1\right) \vee \left(\overline{H}_C \wedge H_A \wedge \mathrm{PWM}_2\right)$$
$$S_{P3} = \left(H_B \wedge \overline{H}_C \wedge \mathrm{PWM}_1\right) \vee \left(\overline{H}_C \wedge H_B \wedge \mathrm{PWM}_2\right)$$
$$S_{P4} = \left(H_A \wedge \overline{H}_B \wedge \mathrm{PWM}_1\right) \vee \left(\overline{H}_A \wedge H_B \wedge \mathrm{PWM}_2\right)$$
$$S_{P5} = \left(H_C \wedge \overline{H}_A \wedge \mathrm{PWM}_1\right) \vee \left(\overline{H}_A \wedge H_C \wedge \mathrm{PWM}_2\right)$$
$$S_{P6} = \left(H_B \wedge \overline{H}_C \wedge \mathrm{PWM}_1\right) \vee \left(\overline{H}_B \wedge H_C \wedge \mathrm{PWM}_2\right)$$
$$S_{N1} = \left(H_A \wedge \overline{H}_B \wedge \mathrm{PWM}_2\right) \vee \left(\overline{H}_A \wedge H_B \wedge \mathrm{PWM}_1\right)$$
$$S_{N2} = \left(H_C \wedge \overline{H}_A \wedge \mathrm{PWM}_2\right) \vee \left(\overline{H}_C \wedge H_A \wedge \mathrm{PWM}_1\right)$$
$$S_{N3} = \left(H_B \wedge \overline{H}_C \wedge \mathrm{PWM}_2\right) \vee \left(\overline{H}_C \wedge H_B \wedge \mathrm{PWM}_1\right)$$
$$S_{N4} = \left(H_A \wedge \overline{H}_B \wedge \mathrm{PWM}_2\right) \vee \left(\overline{H}_A \wedge H_B \wedge \mathrm{PWM}_1\right)$$
$$S_{N5} = \left(H_C \wedge \overline{H}_A \wedge \mathrm{PWM}_2\right) \vee \left(\overline{H}_A \wedge H_C \wedge \mathrm{PWM}_1\right)$$
$$S_{N6} = \left(H_B \wedge \overline{H}_C \wedge \mathrm{PWM}_2\right) \vee \left(\overline{H}_B \wedge H_C \wedge \mathrm{PWM}_1\right)$$

(4)

Equation (4) permits transistor control independent of the direction of rotation.

IV. SIMULATION

The verification of theoretical deliberations featured simulation testing with the use of the ICap4 programs and the Matlab/Simulink package. The ICap program was used to compare the transistor losses in the case of reducing the dc-link voltage. The Matlab package was used to conduct testing of the proposed modulation's properties.

When analyzing the distribution of transistor losses, it is necessary to separate the losses during transistor turn on, conductivity losses and losses during transistor turn off. The conductivity losses in the case of both the described topology and in a star winding connection will be identical (when using identical transistors). Due to the fact that in both types of connection, the current flowing through the windings is identical, the voltage reduction in the semi-conductor structure is the same, therefore the losses are identical. Fig. 7 and Fig. 8 present the waveforms of voltage in the transistor, transistor current, power losses and energy lost in the transistor. Fig. 7 was developed for transistor turn on, whereas Fig. 8 for transistor turn off. The analysis featured a transistor with the parameters Vec = 1200 V, Ic = 50 A.

For both cases (Fig. 7, Fig. 8), the (a) figures are developed with the dc-link voltage of two times smaller than in the (b) figures. Table 1 presents the maximum instantaneous power and lost energy values during turn on and turn off for both intermediate circuit voltages.
As shown by the data in Table 1, the total losses for a single switching period (losses on turn on and turn off, excluding conductivity losses) in the case of a transistor powered with a voltage of 400 V are 2.68 times higher than in the case of a supply of 200 V (with the same current value).
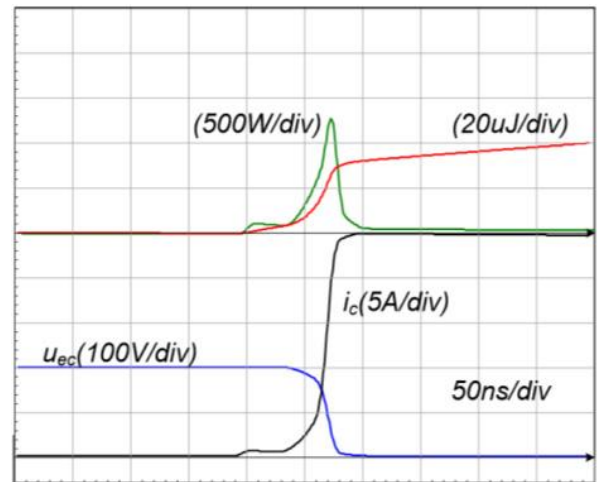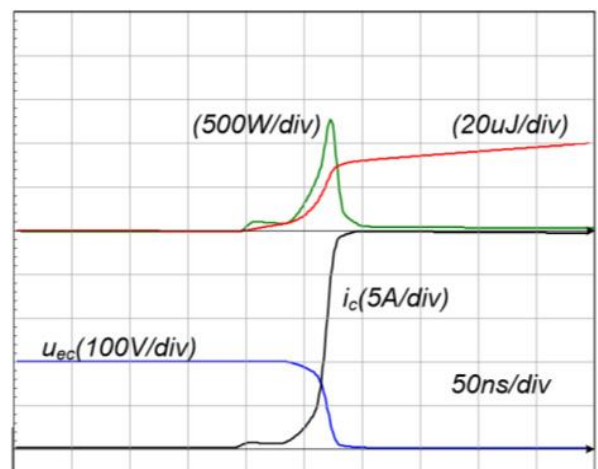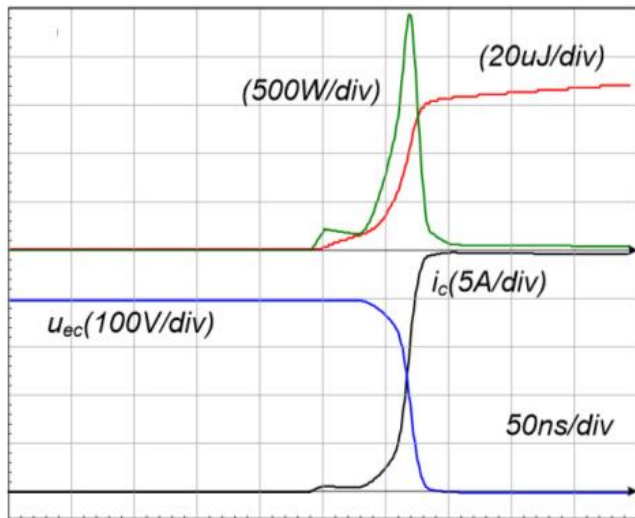

(a)
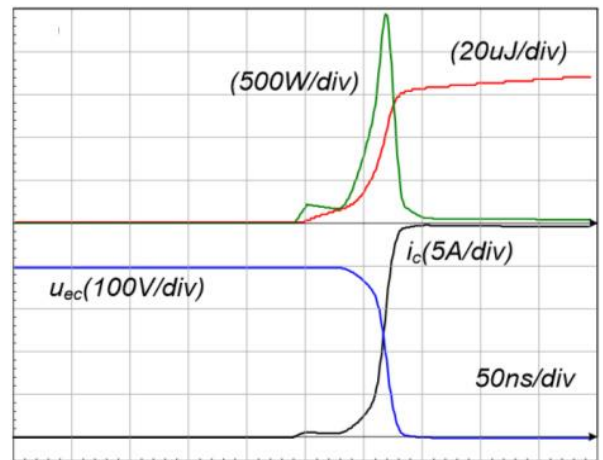
(b)

Fig. 7. Voltage waveforms in the transistor, collector and emitter, transistor current, power and energy losses:
(a) With a dc-link of 400 V voltage; (b) with a dc-link of 200 V voltage

(a)

constancy of the back EMF only the AC component of the current causes the torque ripples.

(b)

Fig. 8. Voltage waveforms in the transistor, collector and emitter, transistor current, power and energy losses:
(a) With a dc-link of 400 V voltage; (b) with a dc-link of 200 V voltage

Table 1. Comparison of transistor losses at emitter-collector voltage reduction

	Turn-on 200 [V]	Turn-on 400 [V]	Turn-off 200 [V]	Turn-off 400 [V]
Power dissipation [kW]	1.19	2.55	1.1	2.3
Energy [μJ]	31.9	67.4	222	791

The described solution utilized a larger number of transistors than in classic supply methods [20–23], moreover there are more transistor switches than in a unipolar modulation [19, 20] (in a typical unipolar modulation, one of the conductive pair transistors is not switched). Simulations using the ICap 4 program were conducted for both supply methods in order to compare the losses when switching all transistors in the tested method and in the classic unipolar technique. The simulations featured the use of the same types of transistors, an identical alternative diagram of the motor made from RLE branches. Table 2 presents the comparison of losses in both methods.

Table 2. Comparation of transistors losses at emitter-collector voltage reduction

Parameter name	Unipolar modulation 400 [V]	Presented solution 200 [V]
3 000 RPM	39.7 [J]	40.1 [J]
10 000 RPM	11.84 [J]	12.05 [J]

The BLDC motor electromagnetic torque is determined on the basis of the following relationship:

$$T_e = \frac{1}{wm}(e_a i_a + e_b i_b + e_c i_c) \qquad (5)$$

Table 3 lists the motor parameters assumed for the simulation. From Equation (5) it follows that, assuming the

Fig. 9 presents the waveforms of the current of one of the phases, back EMF, one of the rotor position signals (Hall sensor), and electromagnetics torque (Te). The waveforms in Fig. 9(a) were developed for the classic unipolar modulation, whereas Fig. 9(b) presents the result of the simulation for the presented solution. The same motor models, transistors and the same simulation parameters (calculation method, integration step) were used in both cases. The waveforms were recorded for the same RPM.

Table 3. List of motor parameters used in the simulation

Item	Type name	Value
1	Power	2 kW
2	Maximum speed	6 000 RPM
3	Inductance	1 mH
4	Rotor moment of inertia	$450 \cdot 10^{-3}$ kg m^2
5	Excitation coefficient	0.04 V/rad/s^{-1}
6	Winding resistance	1 Ω
7	Maximum load torque	3 Nm

As Fig. 9 shows, the AC component of the electromagnetics torque for the classic modulation is equal to 260 mNm, while for the presented solution – 169 mNm. Which means that the ripple decreases by 31.12%. The duration of the torque ripple also decreases from 624 s (classic unipolar modulation) to 272 µs.

For the purpose of more in-depth analysis, Fig. 10 presents zoomed in current waveforms from Fig. 9. The positive waveform fragment was presented.
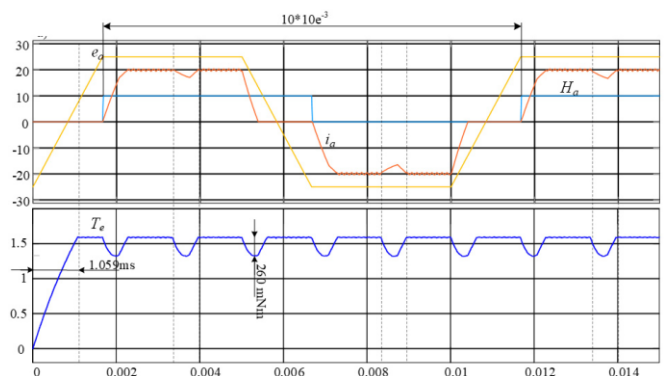
(a)
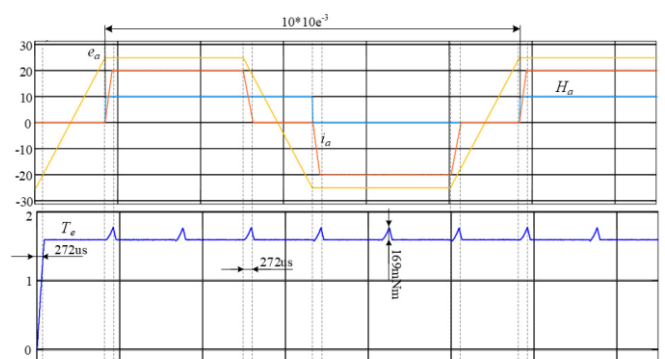
(b)

Fig. 9. Waveforms of the current of a single motor phase, back EMF, position sensor and electromagnetic torque signal recorded for:
(a) The classic unipolar modulation; (b) proposed solution

The comparison of the unipolar modulation and the proposed solution (Fig. 10(a) and Fig. 10(b)) demonstrates that the new solution allows for a significant reduction in the time of current commutation (from $0.4*10^{-3}$ to $0.24*10^{-3}$) and the independent supply of each of the phases prevents the problem of conducting phase current reduction during current commutation in other phases (Fig. 10(a)). Furthermore, Fig. 10 demonstrates a twofold increase in the AC component of the current and twofold reduction in its value (from 1.2 A to 0.6 A). A reduction in the current ripples is achieved thanks to these properties. As Equation (5) shows, a reduction of the AC component of the current causes a reduction in torque ripples.
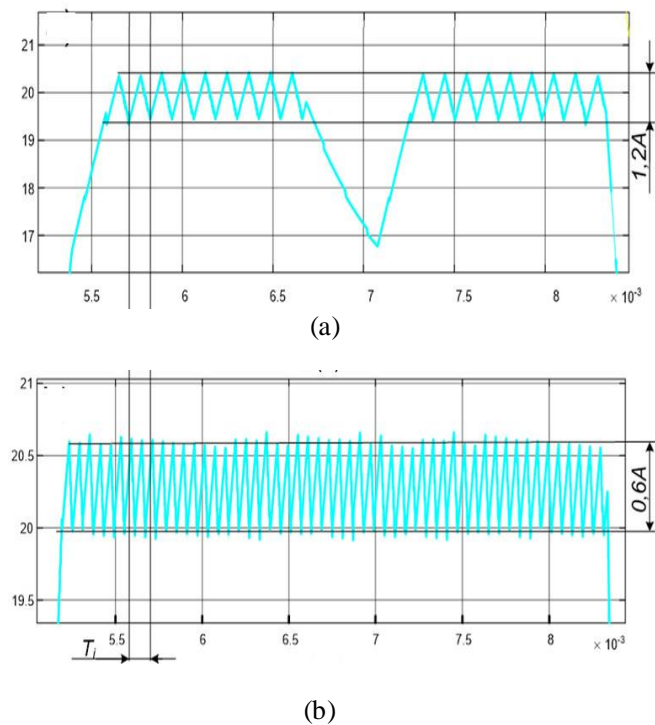

(a)

(b)

Fig. 10. Zoomed in waveforms of the current of a single motor phase developed for: (a) the classic unipolar modulation; (b) proposed solution.

The presented analyses demonstrate that the proposed supply method allows for reducing the current ripples (resulting from the switching operation).

IV. CONCLUSIONS

A method for open-end winding BLDC motor power supply has been presented in the paper. The described power supply method has a number of advantages over the conventional method.

These advantages have been described in Table 4.

	Windings connected in star configuration, unipolar modulation	Open-end windings
Maximum speed possible with the same capacitor voltage	Two times lower than in an open-end winding motor	Two times higher than in a conventionally supplied motor
Phase current ac component frequency	Equal to the transistor switching frequency	Two times higher than the transistor switching frequency
Capacitor current ac component frequency	Equal to the transistor switching frequency	Four times higher than the transistor switching frequency
Current switching between windings	Hindered, takes longer than with open-end winding	There is no problem of taking the current over by successive windings
Torque pulsation resulting from pulsed operation of the power inverter	Pulsation frequency equal to the transistor switching frequency, torque ac component value four times higher than for open-end winding motor	Pulsation frequency four times higher than the transistor switching frequency, torque ac component value four times lower than for conventionally supplied motor
Voltage class of semiconductor elements while maintaining the same rotational speed	At least two times higher than resulting from the BEMF voltage	Greater than the BEMF voltage
Capacitor voltage while maintaining the same rotational speed	At least two times higher than resulting from the BEMF voltage	Greater than the BEMF voltage

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