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# Three switched transistors control algorithm for high efficiency regenerative braking system with BLDC motor

*Algorytm sterowania z trzema przełączanymi tranzystorami dla wysokowydajnego systemu hamowania odzyskowego z silnikiem BLDC*

***Abstract.*** *This paper presents a novel three switched transistors' control algorithm for a BLDC (Brushless Direct Current) motor drive system in the regenerative braking stage. The innovativeness of the suggested method takes an advantage of the phenomenon of reverse drain current conduction in power MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) used to build three-phase full-bridge power converter. The theoretical analysis, and experimental studies show that the new control method increases the efficiency of the converter by 3.5%, compared to the previously used method. The new control algorithm developed by the author has a broad potential in electric vehicle drives and small wind power plants.*

***Streszczenie.*** *Artykuł przedstawia nowy algorytm sterowania maszyny BLDC (Brushless Direct Current) pracującej w trybie hamowania odzyskowego. Innowacyjność proponowanej metody polega na wykorzystaniu przewodzenia wstecznego tranzystorów polowych MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistors), stosowanych w budowie trójfazowych przekształtników mocy. Analizy teoretyczne oraz badania eksperymentalne wykazują, że nowy algorytm sterowania zwiększa sprawność przekształtnika o 3.5% w porównaniu do wcześniej stosowanej metody. Opracowany przez autora algorytm ma duży potencjał zastosowań, szczególnie w pojazdach o napędzie elektrycznym oraz elektrowniach wiatrowych małej mocy.*

**Keywords:** regenerative braking, BLDC machine, three switching transistor control method.
**Słowa kluczowe:** hamowanie odzyskowe, silnik BLDC, sterowanie z trzema przełączanymi tranzystorami.

## Introduction

The classic BLDC (Brushless Direct Current) machine drive systems, commonly used in battery-powered vehicles [1, 2], consists of a three-phase transistor converter and a battery [3]. The three-phase transistor converter is crucial component of the system, as it controls the energy exchange between the machine and the battery. It enables the machine to operate in both motoring and regenerative braking modes, depending on the direction of the energy flow in the system, as illustrated in Fig. 1.

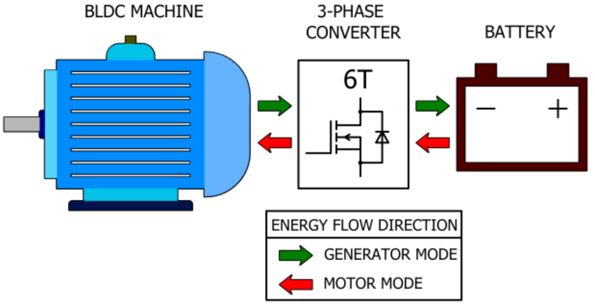



Fig. 1. The classic BLDC machine drive system

During regenerative braking, energy flows from the machine to the battery via the converter. This occurs when the sum of the machine phase voltages is greater than the battery voltage. This is due to the self-inducted voltages generated during the switching of the two machine phases, which correspond to the energy storage stage (energy accumulation in the machine's electromagnetic circuit) and the energy recovery stage (transfer of the accumulated energy to the battery). This principle is used in most control algorithms described in the literature: in the method with single switched transistor [4-6], in the method with transistors switched in a one branch of the bridge [7], and in the method with six switched transistors [8]. Compared to these methods, the method with two switched transistors [9, 10] stands out, in which the battery voltage is summed with the machine phase voltages during the energy storage stage. This allows for more efficient charging of the battery at lower machine speeds and lower duty cycle values.

The previously mentioned algorithms are categorized as classical control methods. Their distinctive feature is that the energy is returned to the battery through the intrinsic diodes of the power transistors. These methods also include the control algorithm with three switched transistors [11, 12]. It operates by short-circuiting the three phases of the machine during the energy storage stage, independently of the rotor position. As a result, there is a simultaneous increase in current in the machine's windings, similar to dynamic braking. Unlike dynamic braking, where the kinetic energy of the rotor is converted only into heat, the use of a transistor converter provides full control over the braking intensity and the amount of energy transferred to the battery.

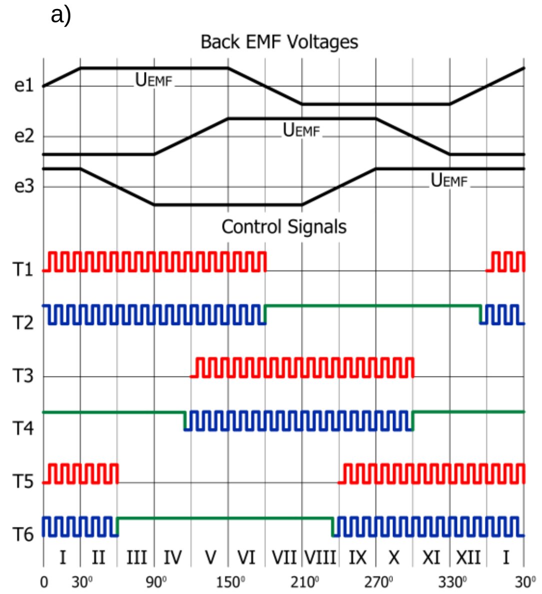
The new control algorithm, which takes advantage of the reverse conduction of power field-effect transistors, along with simulation and experimental studies on converter efficiency, will be presented. The study of the converter efficiency will be conducted with a BLDC machine at power levels of up to 46W, providing scalable results applicable to lightweight, single-track electric vehicles and small-scale wind power plants.

## Description of the new control algorithm

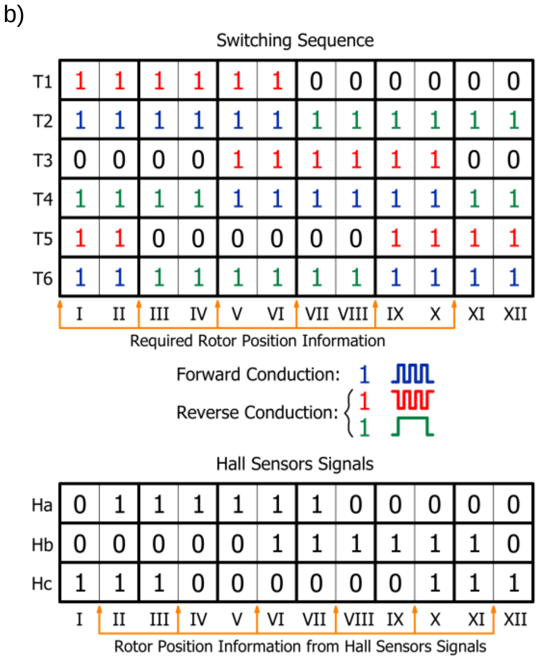
Fig. 2 shows the switching signals and back EMF voltages, the switching table, and the current flow path in the system for the new control algorithm using reverse conduction of field-effect transistors.

This algorithm was developed based on the analysis of the direction of current flow in the converter for both the energy storage and recovery stages. For the method with three switched transistors, this direction is dictated by the sign of the instantaneous machine rotation voltages. On this basis, the sectors of diode pulse conduction (in red) and the sectors corresponding to continuous current flow through the transistor modules (in green) were extracted, Fig. 2a. In these sectors, additional control pulses are used to turn on the transistors for reverse conduction, as shown in Fig. 1b. As seen in Fig. 2b, the new control algorithm requires the identification of the machine shaft position with an accuracy of 300 degree. The required resolution was achieved by using transistor triggering time prediction based on two consecutive Hall sensor readings. When operating in pulse conduction, transistor T1 is switched on in sectors I ÷ VI, T3 in sectors V ÷ X, and T5 in sectors IX ÷ II. In continuous conduction, transistor T2 is switched on in sectors VII ÷ XII, T4 in sectors XI ÷ IV, and T4 in sectors III ÷ VIII. This results in a significant reduction of diode conduction (Fig. 2c), which is the main source of losses in the low-voltage (less then 50V) regenerative braking drive systems.

a)




b)




c)

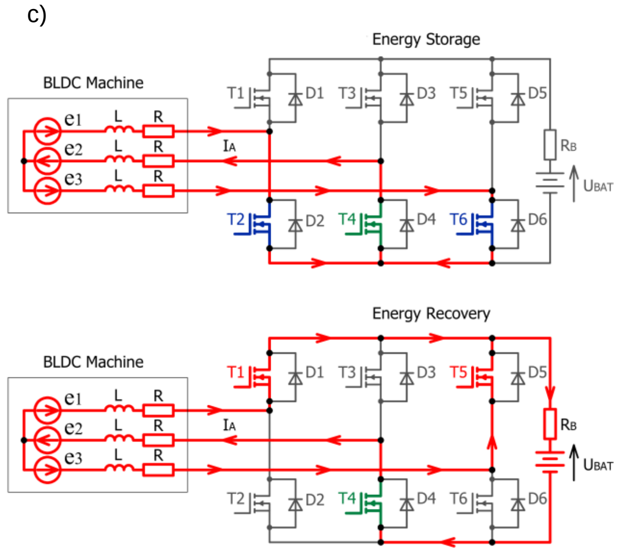


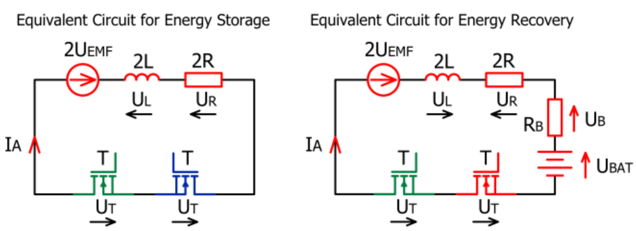

Fig. 2. New regenerative braking control method: a) switching signals and back EMF voltages, b) switching sequence and Hall sensor signals, c) current flow path in the system during energy storage and recovery stages

**Mathematical model**

A mathematical analysis based on the average-value model [13, 14] of a three-phase bridge converter operating with a brushless DC machine in generator mode will be presented. This model was developed based on equivalent circuits determined for the storage and recovery stages. The following simplifications were applied in the mathematical description: the transistors were modelled as elements with a linear current-voltage characteristic and a resistance equal to the transistor's channel resistance in the on-state $R_{DSon}$. Dynamic losses associated with the switching process of the transistors were neglected in the model, as their share in the overall converter losses is marginal - below *2%*. This value was estimated using the MOSFET loss model [15], taking into account the IRFP90N20D transistor parameters, the switched current (*5A*), voltage (*24V*), and a PWM carrier frequency of *20kHz*. The battery was modelled as an ideal DC voltage source $U_{BAT}$ connected in series with the internal resistance of the battery $R_B$. The equivalent circuits corresponding to the current flow path in the converter, machine, and battery for the modified control algorithm with three switched transistors using reverse conduction of power MOSFETs, are shown in Fig. 3.

These circuits result from the instantaneous values of the rotation voltages, for which two (Fig. 3a) or three phases (Fig. 3b) of the machine conduct. Since the contribution of these circuits to the current conduction process is the same, the resultant circuits for both energy storage and recovery stages are as follows:

a)



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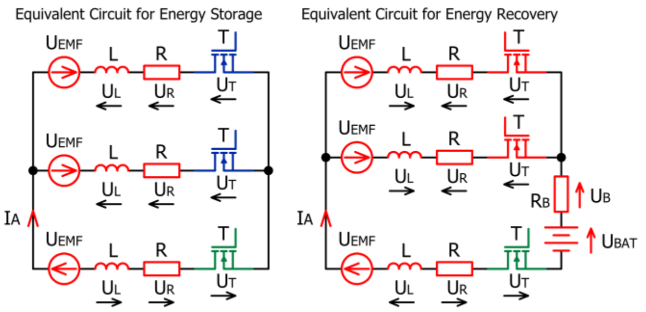



Fig. 3. Equivalent circuits for: a) conduction of two phases of the BLDC machine, b) conduction of three phases of the BLDC machine

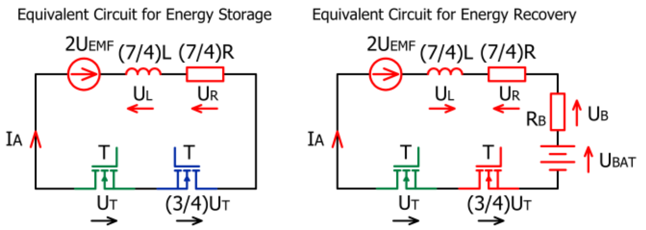



Fig.4. Resultant circuits for the energy storage and recovery stages

The model assumes a constant current value in the machine windings and a trapezoidal shape of the rotation voltages. This results in a rectangular voltage waveform on the equivalent inductance, whose average value, determined over the modulation period *T*, is equal to zero:

$$\frac{1}{T}\int_{0}^{ton} u_L(t)dt + \frac{1}{T}\int_{ton}^{toff} u_L(t)dt = 0 \tag{1}$$

For the energy storage stage, the voltage on the equivalent inductance is represented by the equation:

$$\frac{1}{T}\int_{0}^{ton} u_L(t)dt = \frac{7}{4}D\left(2U_{EMF} - I_A\left(\frac{7}{4}R + \frac{7}{4}R_{DSon}\right)\right)L \tag{2}$$

For the energy recovery stage, the voltage on the equivalent inductance is represented by the formula:

$$\frac{1}{T}\int_{ton}^{toff} u_L(t)dt = \frac{7}{4}(1-D)(2U_{EMF} - I_A\left(\frac{7}{4}R + \frac{7}{4}R_{DSon} + R_B\right) - U_{BAT})L \tag{3}$$

Substituting eq. 2 and 3 into eq. 1 results in an expression for the average current flowing through the windings of the machine $I_A$:

$$I_A = \frac{2U_{EMF} - U_{BAT}(1-D)}{\frac{7}{4}R + R_B(1-D) + \frac{7}{4}R_{DSon}} \tag{4}$$

where: $U_{EMF}$ – back electromotive force (back EMF), $U_{BAT}$ – battery voltage, *R* – generator phase resistance, $R_B$ – internal resistance of the battery, $R_{DSon}$ – static drain-to-source on-resistance of the MOSFET transistor, *L* – generator phase inductance, *T* – period Time, and *D* – PWM duty cycle.

Eq. 4 allows the determination of the power delivered to the battery $P_{BAT}$, and the continuous power losses $P_{LOSS}$:

$$P_{BAT} = I_A U_A (1-D) \tag{5}$$

$$P_{LOSS} = I_A^2 \frac{7}{4} R_{DSon} \tag{6}$$

The efficiency of the converter *η*, which includes continuous losses in the total power balance, is given by the equation:

$$\eta = \frac{P_{BAT}}{P_{BAT} + P_{LOSS}} \tag{7}$$

The converter efficiency equation was implemented in block form in the Matlab-Simulink environment, allowing access to the model variables: the back electromotive force $U_{EMF}$, corresponding to the machine's rotational speed, and the duty cycle *D*. To compare the efficiencies, an analogous equation describing the current flowing through the machine windings for the classical control method was derived:

$$I_A = \frac{2U_{EMF} - U_{BAT}(1-D) - 2U_f(1-D)}{\frac{7}{4}R + R_B(1-D) + \frac{7}{4}R_{DSon}D} \tag{8}$$

Eq. 8 includes the voltage drops across the conducting diodes (equal to the threshold voltage $U_f$), which occur during the energy transfer to the battery. The total continuous losses in the converter (related to the conduction of transistor channels and diodes) are given by the following equation:

$$P_{LOSS} = I_A^2 \frac{7}{4} R_{DSon} D + I_A 2U_f (1-D) \tag{9}$$

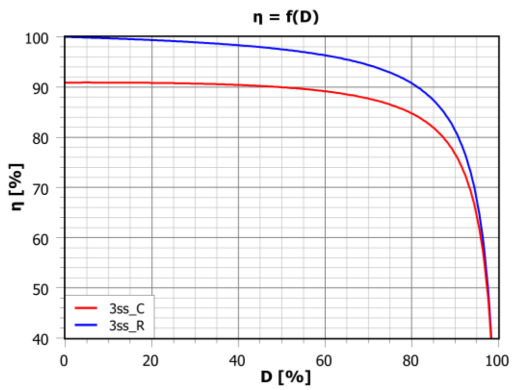
The values of the mathematical model parameters are identical to those used in the experimental tests, as shown in Tab. 1:

Table 1. Mathematical model parameters

| PBL60-78 MACHINE | | | IRFP90N20D TRANSISTOR | | BATTERY | |
|---|---|---|---|---|---|---|
| R [Ω] | $I_A$ [A] | $U_{EMF}$ [V] | $R_{DSon}$ [Ω] | $U_f$ [V] | $U_{BAT}$ [V] | $R_B$ [Ω] |
| 0.4312 | 5 | 12 | 0.023 | 1 | 24 | 0.04 |

Fig. 5 presents comparative simulation results for the converter efficiency as a function of the PWM duty cycle and the machine's rotational speed for: the classical control method with three switching transistors (*3ss_C*) and the improved algorithm using reverse conduction of power MOSFETs (*3ss_R*).

a)



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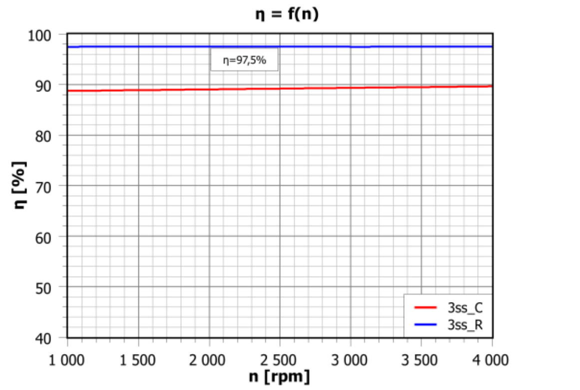


Fig. 5. Converter efficiency as a function of: a) the PWM duty cycle, b) the rotational speed of the BLDC machine at maximum power returned to the battery

Developed by the author control method *3ss_R* ensures high converter efficiency, exceeding *90%* over a wide range of duty cycle values (Fig. 5a). This is due to the absence of diode conduction losses in the converter, which occur with the classical control method. With respect to the machine's rotational speed, the converter efficiency reaches *97.5%*, which is *8%* higher than that of the *3ss_C* control method (Fig. 5b). The constant efficiency results from the unchanged contribution of converter losses in the maximum power returned to the battery in a wide range of machine rotational speeds.

**Experimental results**

The view of the experimental setup for testing the efficiency of a three-phase transistor converter, operating with a brushless DC machine in regenerative braking mode, is shown in Fig. 6.

The research station consists of: (1) the Parvalux PBL60-78 brushless DC machine, (2) the PRMO-65-1101C DC motor, (3) the three-phase converter built with IRFP90N20D MOSFET transistors, (4) a microprocessor based control system with a Microchip dspic33fJ128MC706 controller, (5) two lead-acid CA530 batteries connected in series with a total voltage of 24V, (6) the Agilent MSO7034A digital oscilloscope, (7) the Yokogawa WT1600 power analyser, and (8) a PC used for data collection and archiving.

The diagram of the measurement system is shown in Fig. 7.

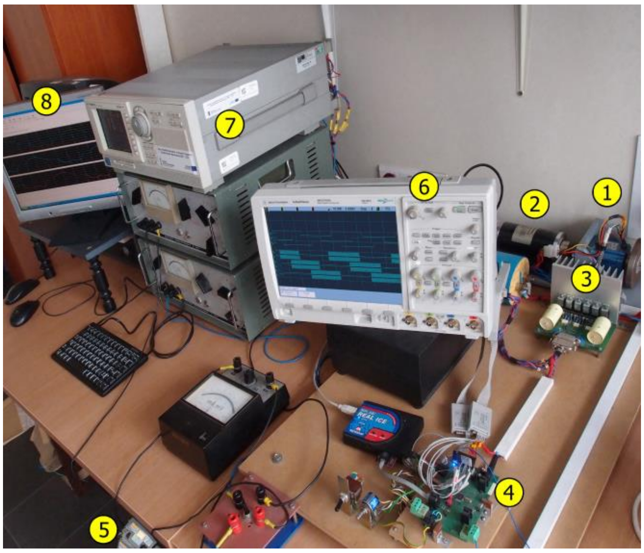


Fig. 6. View of the research station

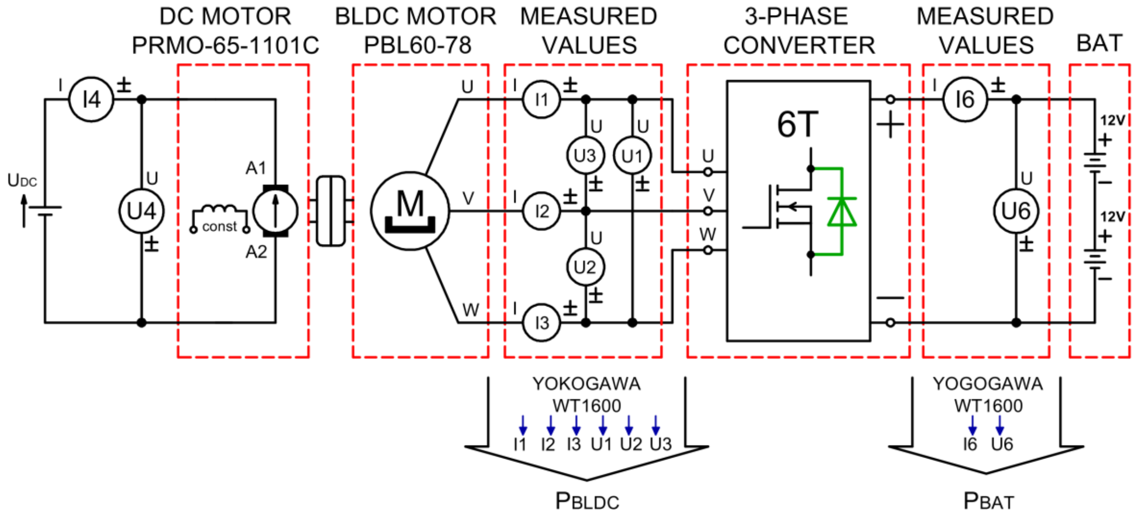


Fig. 7. Diagram of the measurement system

The Yokogawa WT1600 power analyzer is the main component of the measurement system. It measures the instantaneous values of voltages *U1*, *U2*, *U3*, *U6* and currents *I1*, *I2*, *I3*, I6, with a measurement error not exceeding *0.2%*. These values are used to calculate the output power of the BLDC machine $P_{BLDC}$ and the power delivered to the battery $P_{BAT}$. The converter efficiency is given by:

$$\eta = \frac{P_{BAT}}{P_{BLDC}} 100\,\% \tag{10}$$

Example waveforms of phase-to-phase voltages and phase currents of the machine obtained for a rotational speed *n=3000 rpm*, duty cycle *D=63.4%*, machine output power $P_{BLDC}=10.75W$, and power delivered to the battery $P_{BAT}=10W$, are shown in figs 8 and 9.

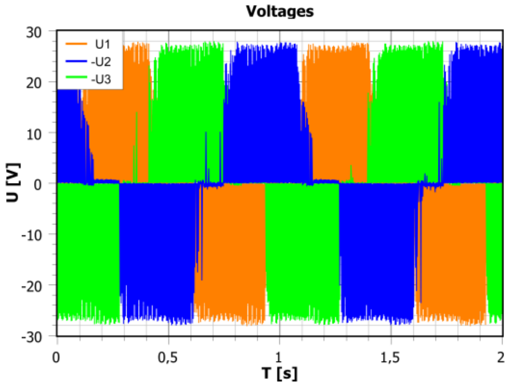


Fig. 8. Waveforms of phase-to-phase voltages of the machine

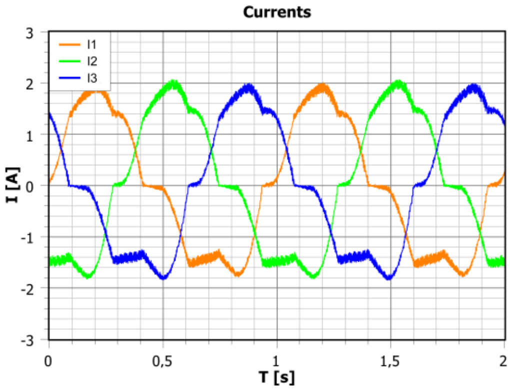


Fig. 9. Waveforms of phase currents of the machine

Fig. 10 shows the converter efficiency as a function of the PWM duty cycle.

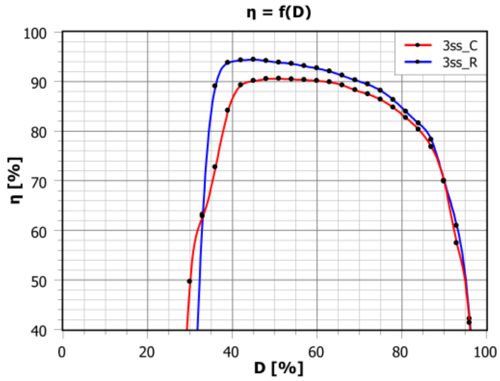


Fig. 10. Converter efficiency as a function of the PWM duty cycle at maximum power returned to the battery

The introduction of reverse conduction of field-effect transistors has resulted in improved converter efficiency for a duty cycle range of *35 ÷ 90%* (Fig. 9). The average increase in efficiency within this range was *3.6%*. At lower duty cycle values, a greater increase in converter efficiency is observed. This is due to the high contribution of diode conduction losses to the total converter losses in the classic control method. As the duty cycle increases, this contribution decreases, leading to a lower increase in converter efficiency.

Fig. 11 shows the converter efficiency as a function of the rotational speed of the BLDC machine.

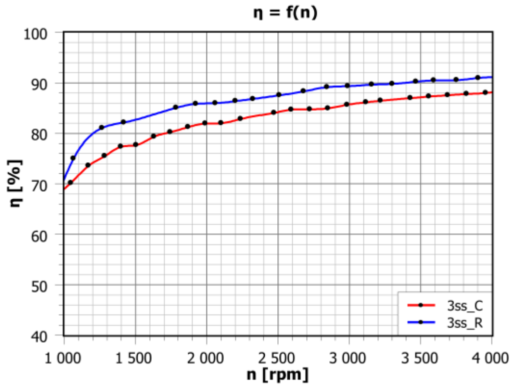


Fig. 11. Converter efficiency as a function of the rotational speed of the BLDC machine at maximum power returned to the battery

Efficiency improvements are also noted with respect to the machine's rotational speed (Fig. 10). A *3.4%* increase in average efficiency was obtained over a wide range of rotational speeds: *1000 ÷ 4000 rpm*.

## Summary

The paper describes in detail a new control algorithm for the regenerative braking stage of a BLDC motor, supported by both simulation and experimental studies. The primary advantage of the proposed control method is the higher efficiency of the converter over a wide range of machine speed variations (*3.8%* better in average than the classic control method). Additionally, the algorithm does not require a faster microcontroller. However, the solution has certain drawbacks, such as the necessity of a Hall sensor and a rotor position prediction algorithm. Nonetheless, given that most BLDC machines are factory-equipped with Hall sensors, this requirement does not incur additional costs. The proposed new control method is dedicated to low-voltage (up to approximately *50V*) drive systems. This primarily applies to single-track vehicles, such as electric scooters and electric bicycles, where the motor power is typically in the range of *250W ÷ 3kW* - depending on the design and purpose of the vehicle. In such systems, the main source of power losses (occurring in the regenerative braking state) are the diode switches, which participate in the process of returning energy from the electromagnetic circuit of the BLDC machine to the battery. Replacing diode conduction with reverse-conducting transistors significantly reduces these losses, increasing the converter efficiency. Another potential application area for the developed control algorithm is low-voltage small-scale wind power plants, with power ratings of up to *5kW*. However, at higher power levels, the benefits of reverse conduction diminish. This is due to the characteristics of the current-voltage curves of field-effect transistors and their intrinsic diodes, which, at higher power levels become increasingly similar, limiting the advantages of the new control method.

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