PSpice model of a brushless machine operating in a generator mode by converting the inverter in a boost converter

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B*rushless machines are increasingly used in various fields of engineering, due to their simplicity, reliability and easy manner for control. The present paper is focused on the machine operation in a generator mode. Modeling and simulating of a brushless machine enable determining the optimal way of managing the machine in a motor and in a generator mode. The paper considers the PSpice model of a brushless machine. The machine operates in a generator mode by converting the inverter in a boost converter. The conditions for the transition from a motor mode to a generator mode of the brushless machine are analyzed. It is estimated the impact of the supply voltage of the battery and the speed of the machine on the returned amount of energy to the power supply. The purpose of the paper is to simulate the operation of a brushless machine in a generator mode by converting the inverter in order its usage in an electric vehicle.*

PSpice модел на безчеткова машина, работеща в генераторен режим чрез преобразуване на инвертора в повишаващ преобразувател (Иван П. Мараджиев, Емил И. Динков). *Поради своята простота, надеждност и прост начин за управление, безчетковите машини намират все по-голямо приложение в различни области на техниката. Съществен интерес представлява възможността за работа на такъв тип машини в генераторен режим. Моделиране и симулиране на безчеткова машина предлага удобен начин за определяне на оптималния начин за управление на машината в двигателен и генераторен режим на работа. В настоящия доклад се разглежда PSpice модел на безчеткова машина. Машината се поставя в генераторен режим на работа, чрез преобразуване на инвертора в повишаващ преобразувател. Направен е анализ на условията за преминаването от двигателен в генераторен режим на безчетковата машина. Анализирано е влиянието на стойността на захранващото напрежение на акумулатора и скоростта на въртене на машината върху количеството върната енергия. Изследванията са направени с оглед използването на безчетковите машини в електрически превозни средства.*

Introduction

Brushless machines are used in different areas, such as systems of electrical actuators, motor industry, and medical equipment, instrument engineering and household appliances. Distinctive features of these machines are their simple construction, simple operation and easy maintenance. Brushless machines are highly effective. In principle, their efficiency is around 70%. In some motors with capacity of several hundred watts it reaches 85% [1].

This paper examines a developed model of a brushless DC electric motor (BLDC motor) with a trapezoidal shape of reverse electromotive tension. Mathematical equations, describing the processes in the brushless motor, are used in the model.

Authors like Krishnan works on a modeling of brushless machines in the Matlab programming environment [2]. In addition the library Electric Drives / AC drives of Simulink offers a full model of a brushless machine. Other scientists, like Mallik and Dhawan develop a PSpice model of a brushless machine, working in a motor mode [3]. Present experiments are made using their model as some changes are made in the control scheme.

We are interested in the working of a brushless machine in generator mode and the process of transferring energy from the machine to the power source. On this base, an algorithm is developed for switching machine operation from a motor mode to a generator mode by converting the three-phase inverter into a boost converter. The aim is to transfer energy from a lower voltage source to a higher voltage source. This technique can be used in electric vehicles in order to increase the distance covered on a single charge of the battery. It may also find application in renewable energy systems.

Structure and mathematical model of a brushless machine

By powering the brushless motor, several phenomena should be considered. Fig.1 shows an equivalent electric model of a brushless machine.

When the rotor of the brushless machine is stationary, the impedance of the coil resists current

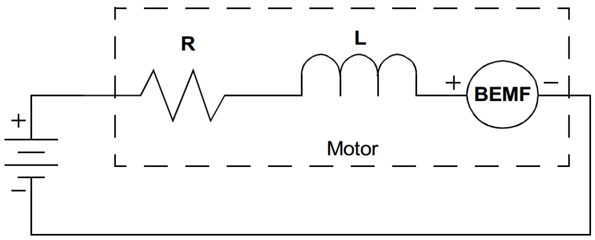

Fig. 1.

flow through the coil. The active resistance R and the inductance L are very small, so that the starting current can be much higher if not limited. When the rotor rotates, the permanent magnet inside moves along the stator windings and induces in them reverse electrical voltage (E). This voltage is opposite to the voltage that powered the coil according to Lenz's rule, and reduces the current. The back e.m.f. E is directly proportional to the speed of the motor – RPM . It is determined by the voltage constant K_E of the motor [5].

(1) $$E = RPM / K_E$$

The current I that the motor consumes is in direct proportion to the load torque of the motor shaft M [1]. The current of the engine is defined by the constant for the moment of the motor K_M.

(2) $$M = K_M \times I$$

This allows the working out of a mathematical model for a brushless motor. For this purpose a diagram of a three-phase motor, powered by a three-phase inverter is used. It is shown on Fig.2.

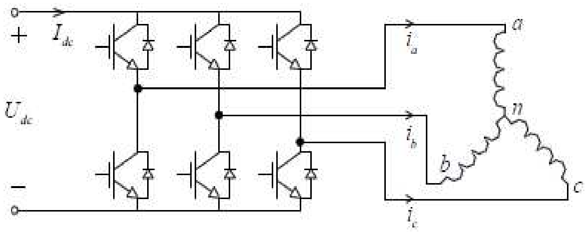

Fig.2.

Voltages across the motor windings are[4]:

(3) $$u_a = Ri_a + L\frac{di_a}{dt}$$
$$u_b = Ri_b + L\frac{di_b}{dt}$$
$$u_c = Ri_c + L\frac{di_c}{dt}$$

where u_a, u_b and u_c – phase voltages, i_a, i_b and i_c – phase currents.

Due to the permanent magnet mounted in the rotor, electromotive voltages e_a, e_b and e_c are with trapezoidal shape, as shown on Fig.3.

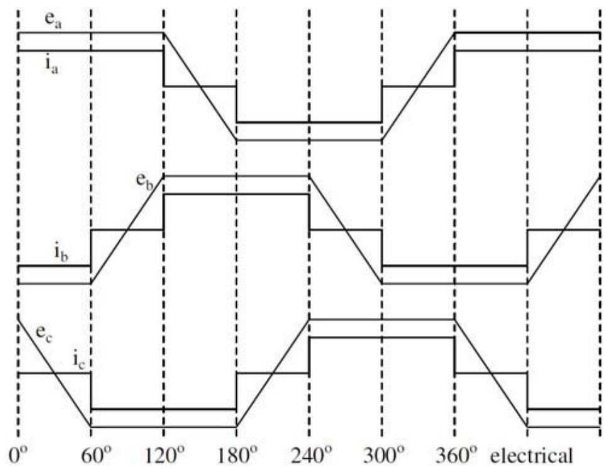

Fig. 3.

They are expressed by the equations [4]:

(4) $$e_a(t) = K_E.\ (\Theta).\omega(t)$$
$$e_b(t) = K_E.\ \left(\Theta - 2\frac{\pi}{3}\right).\omega(t)$$
$$e_c(t) = K_E.\ \left(\Theta + 2\frac{\pi}{3}\right).\omega(t)$$

The torque can be expressed by the formula:

(5) $$M = (e_a i_a + e_b i_b + e_c i_c)/\omega\ .$$

PSpice model of a brushless motor

The model of a brushless motor consists of a three-phase inverter powered by a DC voltage source [3]. The voltage source is a rechargeable battery.

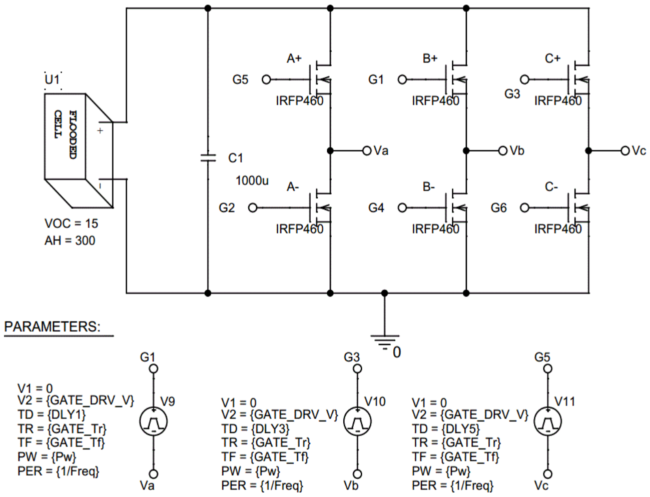

Fig. 4.

Upper transistors in the arms of the inverter are controlled by signals, generated by the sources of impulse voltages V9, V10 and V11 (Fig. 4). Lower transistors in the arms of the inverter are controlled by PWM signals with frequency of 20 kHz (Fig. 5).

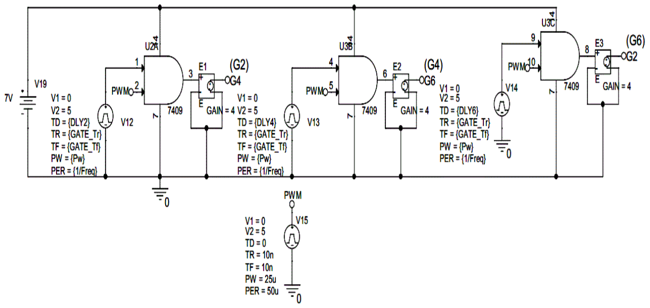

Fig.5.

Motor windings are represented with their inductances L_MOT 0.87mH and active resistances R_MOT 0.22Ω (Fig.6). Back e.m.f. in the windings are modeled with impulse voltage sources V1 and V2 for phase A, V3 and V5 for phase B and V4 and V6 for phase C.

The one of the sources for the one of the phases forms the positive half-wave of trapezoidal e.m.f., while the second one forms the negative one. The value of the amplitude of the back e.m.f. A is set in the PARAMETERS element and for speed of rotation 4000 rpm equals to 7.6V.

The speed of rotation is set by the frequency of transistors switching Freq and for 4000 rpm is 133Hz.

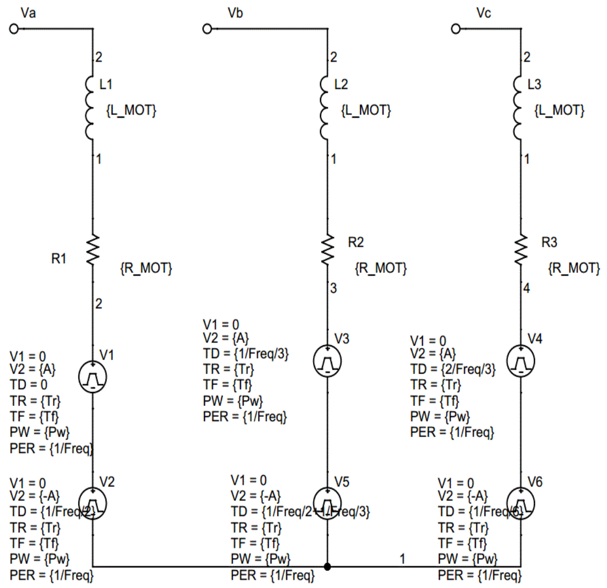

Fig. 6.

The parameters of the sources are set according to the following formulas in the PARAMETERS element [4]:

Tr = 1/Freq/12; Tf = 1/Freq/12; Pw = 1/Freq/3; GATE_Tr = 10uS; GATE_Tf = 10us; DLY1 = 0; DLY2 = DLY1+1/Freq/2; DLY3 = DLY1 +1/Freq/3; DLY4 = DLY1 + 1/Freq/3 +1/Freq/2; DLY5 = DLY1 + 2/Freq/3; DLY6 = DLY1 + 2/Freq/3 + 1/Freq/2; GATE_DRV_V = 15V.

A six step algorithm is used for switching the transistors in the inverter: A + B-, A + C-, B + C-, B + A-, C + A-, C + B-, as with index "+" upper transistors are represented and with index "-" lower. In this way the brushless machine works as a motor.

To work as a generator, the inverter of the brushless machine can be converted in a boost converter. For this purpose, all top switches are kept turned off. Back e.m.f, generated in the winding of phase A of the motor acts as a supply voltage of a boost converter, comprised of the inductivity of the winding, the lower transistor of the arm of the inverter for phase A and the reverse diode of the upper transistor of the same arm. Back e.m.f. increases and energy flows to the battery that powers the inverter. The process is similar for the remaining two phases. Thus, there occurs three boost converters connected to a single load.

In the described model of operation it is not possible to transform the inverter in a boost converter. It can be seen on Figure 7. In black color the back e.m.f. in phase A and the modulating impulses for the lower transistor of arm A of the inverter. The controlled pulses are submitted when the back e.m.f. is negative.

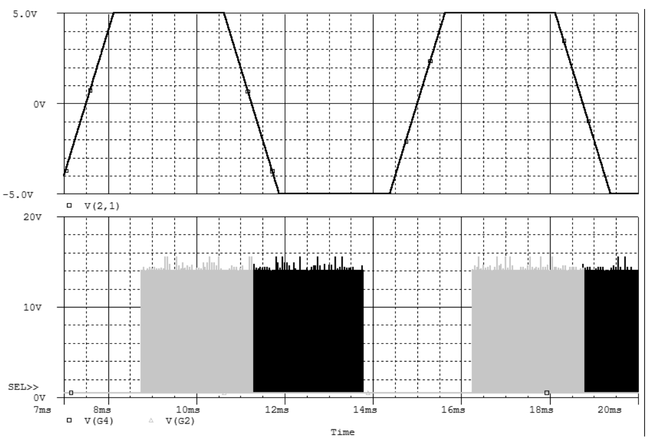

Fig. 7.

In order to create working conditions for the boost converter, the control signals must be submitted when the back e.m.f. is positive. On the same figure in gray color control pulses for the lower transistor of phase C are shown. They are submitted when the back e.m.f. of phase A is positive. Therefore, to transform the inverter in a boost converter, control signals for the lower transistors must be submitted with a reverse phase sequence.

On Figure 5, the control signals for the lower transistors in generator mode are shown in brackets. Waveforms of the back e.m.f. and control pulses for the lower transistor of phase A in a generator mode are shown on Figure 8.

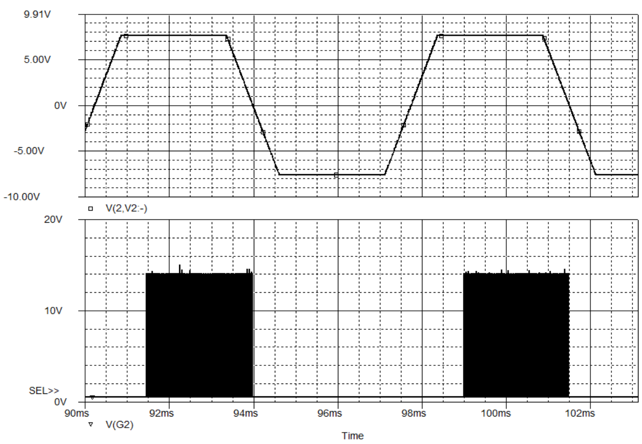

Fig. 8.

Results

Simulations are made at 2500 rpm, 3400 rpm and 4000 rpm. At these rpm amplitude value of back e.m.f. equals 4,75 V, 6,463 V and 7.6V. During these simulations, the duty cycle of control signals of lower transistors is changing from 0% to 99%.

The effective values of the current flowing to the battery and the voltage on it are listed in Table 1. On Figure 9 it is shown the variation of the effective value of the current to the battery at different speeds of rotation and a changing duty cycle of control signals.

Table 1

4000rpm		U_{BAT}=10.8V	4000rpm		U_{BAT}=12V
I [A]	U [V]	D [%]	I [A]	U [V]	D [%]
0.57	11.2	0	0.345	12.2	0
0.7	11.3	10	0.5	12.4	10
0.85	11.3	20	0.68	12.4	20
0.99	1.38	30	0.82	12.5	30
1.1	11.4	40	1	12.6	40
1.2	1.38	50	1.1	12.5	50
1.2	11.4	60	1.2	12.5	60
1.2	11.3	70	1.2	12.5	70
1.2	11.2	80	1.2	12.4	80
1	11	90	0.9	12.3	90
0.3	10.9	99	0.32	12.1	99
4000rpm		U_{BAT}=15V	3400rpm		U_{BAT}=12V
I [A]	U [V]	D [%]	I [A]	U [V]	D [%]
0	15	0	0.001	12	0
0.1	15.1	10	0.2	12.1	10
0.28	15.2	20	0.35	12.2	20
0.5	15.2	30	0.5	12.3	30
0.6	15.4	40	0.6	12.4	40
0.85	15.4	50	0.8	12.4	50
1	15.4	60	1	12.4	60
1	15.4	70	0.96	12.4	70
1	15.4	80	0.95	12.4	80
1	15.3	90	0.9	12.4	90
0.3	15	99	0.5	12.1	99
2500rpm		U_{BAT}=12V			
I [mA]	U [V]	D [%]			
0	12	0			
0.02	12	10			
0.02	12	20			
0.04	12	30			
0.18	12.1	40			
0.24	12.1	50			
0.48	12.1	60			
0.49	12.1	70			
0.5	12.2	80			
0.5	12.2	90			
0.35	12.1	99			

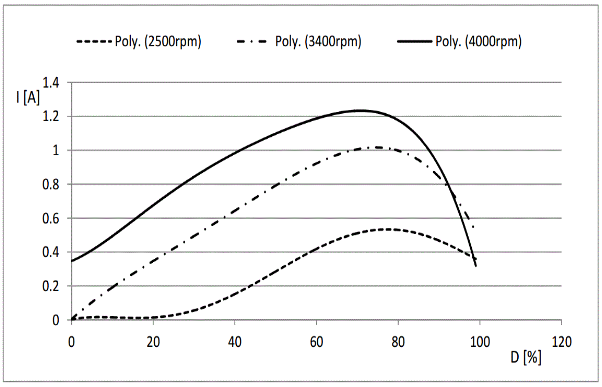

Fig.9.

On Figure 10 it is shown current variation at a different battery voltage 10,8 V, 12V and 15V, which values correspond to a discharged lead accumulator, an accumulator in normal operating mode and an accumulator with a maximum operating voltage.

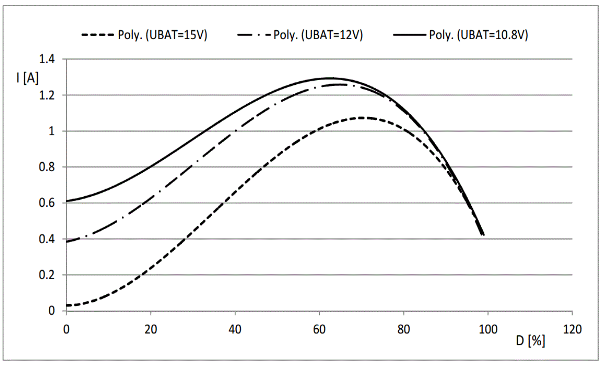

Fig.10.

Results show that at a low rpm and a low duty cycle, the current flowing to the battery is less than at higher rpm. This current is higher when the duty cycle is increasing, as at ratio of 55% to 85% the current is highest. The increase of a duty cycle allows a charging at low rpm. In cases of a duty cycle greater than 85%, the current considerably falls.

As well as for low battery the current flowing thereto is greater than the current flowing to a charged battery. If the value of the battery voltage is 15V, the current at low duty cycle is with significantly low value than current in battery voltage of 10,8 V and 12V. By increasing the duty cycle the returned energy in battery increases.

Conclusion

The described PSpice model of brushless machine and the transformation of an inverter in a boost converter prove that a return of energy to the battery that power the inverter can be achieved. The battery voltage is substantially greater than the voltage generated in the windings of the machine, but by converting the inverter there is a return of energy at a different speed of rotation and at a different level of charge of the battery.

The achieved results are close to an ideal case, because the increasing duty cycle in a real generator will create a moment of resistance and speed will be reduced. When the experiment of the electric drive with a brushless machine is carried in a real situation, the duty cycle will vary in more narrow ranges. In the simulated model running speed is constant across the whole range of variation of the duty cycle.

The results of the simulation of the PSpice model of a brushless machine in a generator mode are a base for a future research. Under construction is a motor-generator group composed of a brushless machine and a direct current machine that will confirm the results of experiment model.

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