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Low Cost High Efficiency Unipolar Converter for Permanent Magnet Synchronous Motors

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Professional paper

This paper describes the development of a low cost power converter for permanent magnet synchronous motors (PMSM). Only low side switches are used for motor control similar to unipolar brushless DC (BLDC) converters but much higher efficiency is achieved because no snubber circuit is needed. Instead of being dissipated on snubbers the energy is re-circulated over a buck converter. So the converter topology can be shown as a multi »phase« BOOST – single »phase« BUCK converter (C-dump converter) where the PMSM windings represent the inductors of the boost part. PMSM control is performed with signals derived from embedded Hall sensors and developed low cost circuitry.

Key words: PMSM, boost converter, buck converter

1 INTRODUCTION

Usage of permanent magnet synchronous machines constantly rises in the last years because of their higher efficiency, longer lifetime, less copper and decrease of magnetic material prices. However total drive cost is composed of motor and the corresponding control electronic. For small drives the control electronic cost for the PMSM [1, 2] can be dominant, so a good performance/cost ratio has to be found for low cost applications.

For control of PMSM the rotor magnetic flux orientation has to be known. The rotor orientation can be derived from an appropriate sensor or an observer. Hall-effect based sensors are most used for rotor flux orientation (angle) measurement position due to their cost and simplicity of use. The Hall sensors are mounted in the BLDC and sense the magnetic field generated by the permanent magnets of the rotor. Three of these sensors give a resolution of 60° which is used for BLDC motor rotor position measurement. When a rotor position (angle) observer is used there is no need for rotor orientation measurement sensors but the position observer requires a high performance controller, exact measurement of electric variables (current and voltage) and machine parameters (winding resistance, inductance ...). Due to this the cost of control electronic increases even if position sensors are not needed.

The simplest converter structure for a PMSM is when switching elements are connected in series with motor windings. In such configuration the turn off voltage spikes produced by the energy stored in the winding inductance [3] have to be controlled. This is the reason that such converters need snubber-circuits, which dramatically reduce the converter efficiency. In order to avoid this undesired phenomena another converter structure as suggested in [4, 5], must be considered. The chosen converter structure should enable the returning of the trapped inductor energy to the power supply capacitor (Figure 1).

This paper considers a low cost converter for BLDC-like control of PMSM based on boost and buck converters. The BLDC-PMSM control is studied first by simulation and afterwards by measurement on experimental prototype. The whole converter consists of low cost discrete elements, logic gates and operational amplifiers.

2 CONVERTER STRUCTURE

A) Power stage

The power stage of the converter is organized as a unipolar BLDC-PMSM converter where the switching elements are connected in series with motor windings as shows Figure 1. The common (star) point of motor windings is connected to the positive DC-Link + U_{DC1}. The switching elements are connected to the negative DC-Link so only low-side driver (triggering) circuits are needed for motor control. The converter for BLDC-PMSM

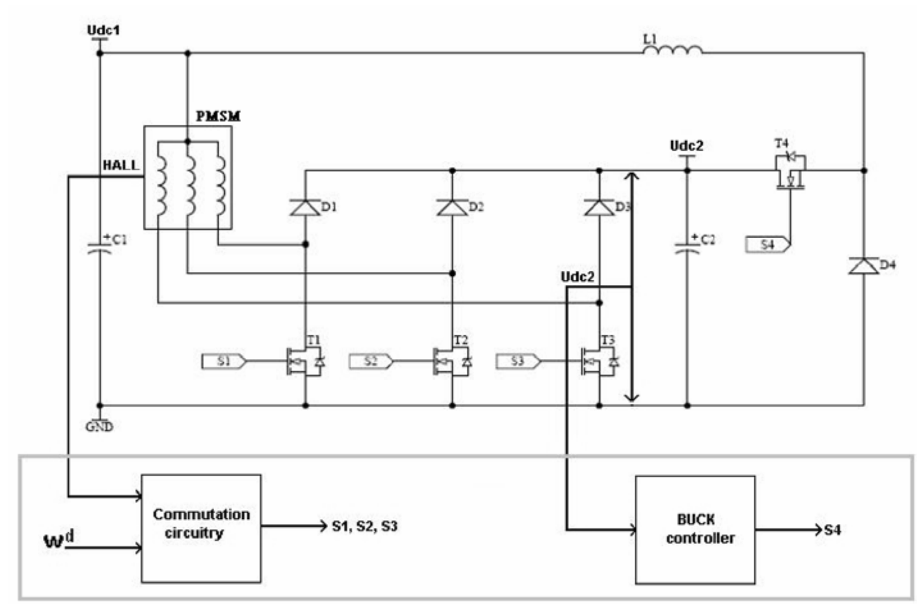

Fig. 1 Converter topology

drive can be described as a multiphase boost converter and additional buck converter. This converter structure operates with two DC-Links. The first DC-Link (U_{DC1}) feeds the motor windings with energy when the switches $S1$, $S2$ and $S3$ enable this. When the switches $S1$, $S2$ and $S3$ are turned off the energy stored in the windings inductance is transferred to the second DC-Link (U_{DC2}).

B) Pulse width modulation (speed control)

The machine is voltage controlled. This gives the ability to control the speed with the duty cycle d of the pulse width modulated signal (1). Equation (1) shows the dependence of motor speed versus voltage and current,

$$\omega = \frac{U_{DC1}d - i_1 R_{S1} - L_{S1}\dfrac{\mathrm{d}i_1}{\mathrm{d}t}}{K_e} \tag{1}$$

where U_{DC1} is first DC-link voltage, i_1 is current trough winding one, R_{s1} is winding resistance, L_{s1} is winding inductance and K_e is the voltage constant of the machine. Current control was not implemented in terms of cost reduction.

For commutating the windings, signals from three embedded Hall sensors are used. The commutation angle depends on the Hall sensor position and the permanent magnets magnetic field. By using signals of the Hall sensors the PWM signal is distributed to the appropriate power transistor. The PWM signal is obtained by circuit shown in Figure 2 where the speed reference (Ref) is com-

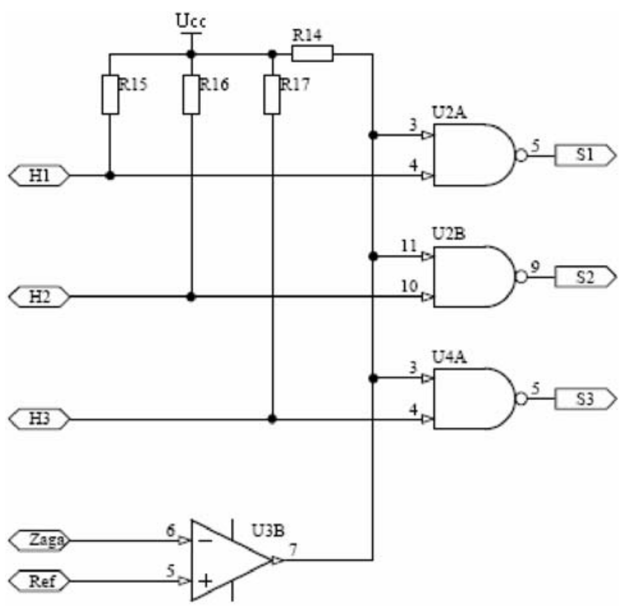

Fig. 2 Commutation circuit

pared to a saw-tooth signal (Zaga). The switching frequency depends on the saw-tooth signal.

C) BUCK Converter control

The buck converter controls the second DC-Link voltage U_{DC2}. In order to implicit control the winding currents without current feedback the sum of the first DC-Link UDC1 and the back emf voltage of the winding (u_s) always need to be below the second DC-Link U_{DC2} voltage (2).

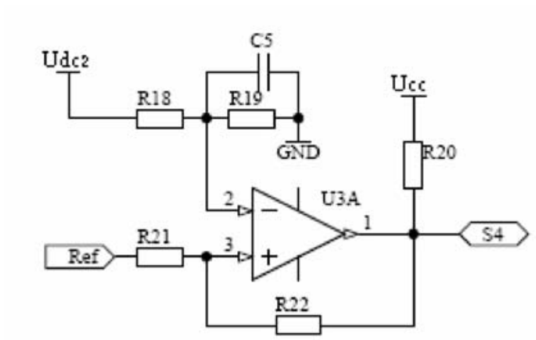

Fig. 3 BUCK controller

$$
\begin{array}{lll}
i_1 > 0 & & \\
 & & U_{DC2} > U_{DC1} + u_{S2} \\
i_2 = 0 & \rightarrow & \\
 & & U_{DC2} > U_{DC1} + u_{S3} \\
i_3 = 0 & &
\end{array} \qquad (2)
$$

If (2) is not fulfilled »uncontrolled« currents will flow through not commutated windings and cause additional torque ripple, noise and reduced efficiency of the whole drive. Voltage control of the second DC-Link is achieved with a simple hysteresis controller which is build with a single comparator as shown in Figure 3. Transistor $T4$ is controlled by the comparator signal. The switching frequency of the BUCK converter is defined with the allowed voltage hysteresis u_h, capacitance of the second DC-Link, inductance of L_1, inductance of the motor winding LS, winding current i_s and motor speed ω.

D) MOSFET drivers

In order to switch the power MOSFET's the control signals have to be amplified in the driver (triggering) stages. The gate of MOSFET's behaves like a capacitor [3, 6], because there is a dominant parasitic capacitance present in the circuit. To turn on or off the MOSFET the capacitance C_{GS} has to be charged or discharged respectively. So the driver stage must be able to deliver the appropriate current and voltage for turning on or off process. The faster the gate is charged or discharged the smaller are the switching loses on the device. But on the other hand sharper slopes result in higher electromagnetic interference (EMI) to be emitted in environment. The triggering circuit for switching on and off the low side switches ($S1$, $S2$ and $S3$) is shown in Figure 4. A low cost solution for the driver stages is chosen by using only one bipolar transistor $T1$ and some passive elements. So in order to turn on and off the $S1$, $S2$ and $S3$ three such driver stages are necessary.

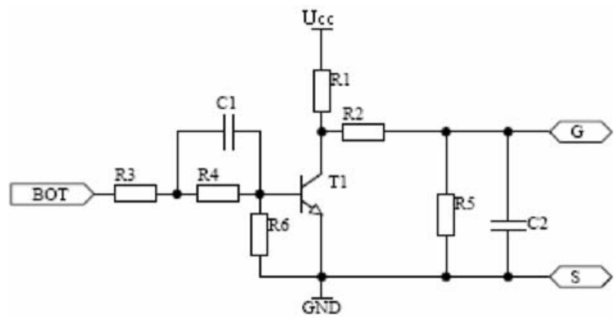

Fig. 4 Low side driver

The converter also contains a high side power switch (buck converter, switch $S4$). In order to turn on and off the $S4$, the gate signal has to be level shifted in relation to the MOSFET source potential. For level shifting an opto-coupler is used in the high side driver stage as shown in Figure 5. To turn on or off the high side MOSFET, the driver stage always needs to have the appropriate voltage. To generate this voltage a bootstrap circuit is used so the capacitor $C3$ is charged over the diode D1 to U_{CC} when transistor T4 is turned off and the diode D4 conducts. Afterwards the capacitor $C3$ is level shifted with the source of the high side MOSFET. To enable the first turn on of the high side

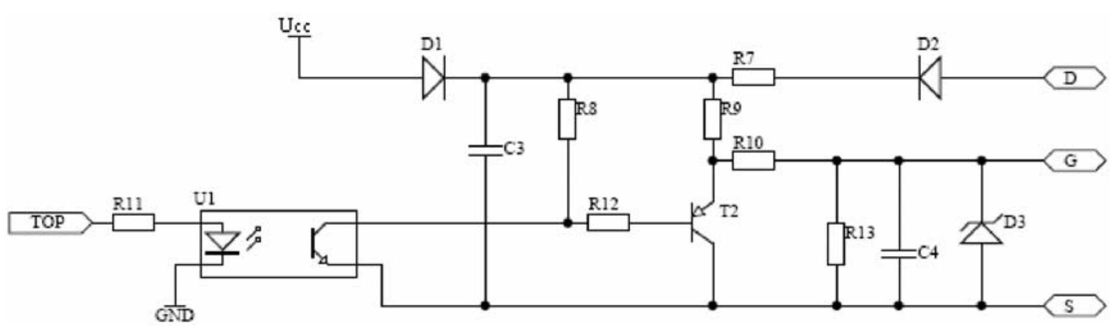

Fig. 5 High side driver

switch T4 the capacitor $C3$ is also charged over R7 and D2 from the second DC-Link. When bootstrap becomes active the influence of charging $C3$ from the second DC-Link is negligible because of the time constant of the charging circuit. The high side driver stage also contains a Zener diode to protect the MOSFET by limiting the gate source voltage. The switching slopes are controlled with $R1$, $R2$, $C2$ for the low side switches and with $R9$, $R10$, $C4$ for the high side switch.

3 SIMULATION RESULTS

The low cost converter was first studied by simulation under the frame of MATLAB/Simulink program. The real circuit parameters were chosen for simulations which mean the winding series resistance and ESR was considered for inductors and capacitors respectively. Results show expected behavior of the converter. Figure 6: **Induced back EMF and phase currents** shows the induced back emf and the winding (phase) currents.

Phase currents i_1, i_2, i_3 are implicitly controlled as was predicted by (2). Back emf e_1, e_2, e_3 have the sinusoidal wave shapes. The circumstances on the second DC-Link are shown in Figure 7. The voltage U_{DC2} is regulated to the desired value $U_{DC2}{}^{d}$ by the buck converter.

4 EXPERIMENTAL RESULTS

The prototype of BLDC-PMSM drive and appropriate power converter were build in order to verify the proposed control algorithm. Experimental results show that the whole system is working as expected. Figure 8 and Figure 9 show the experimental results. Current magnitude variation is caused by the asymmetry of the PMSM and position of Hall sensors. Experimental and simulation results are in a good accordance. Back emf e_1, e_2, e_3 are not sinusoidal because the prototype PMSM has not pure sinusoidal back emf. Also switching noise is visible on the windings emf's when one of the low side switches $T1$, $T2$ or $T3$ is active.This happens because of the magnetic coupling of the

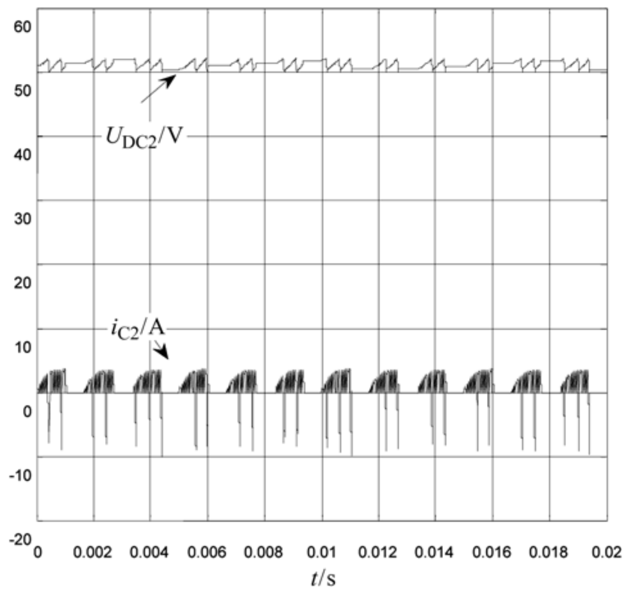

Fig. 7 Voltage of the second DC-Link U_{DC2} and i_{C2} current

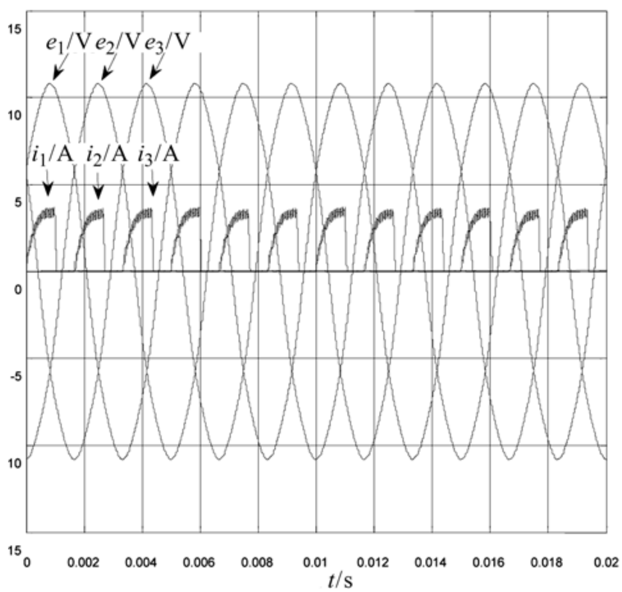

Fig. 6 Induced back EMF and phase currents

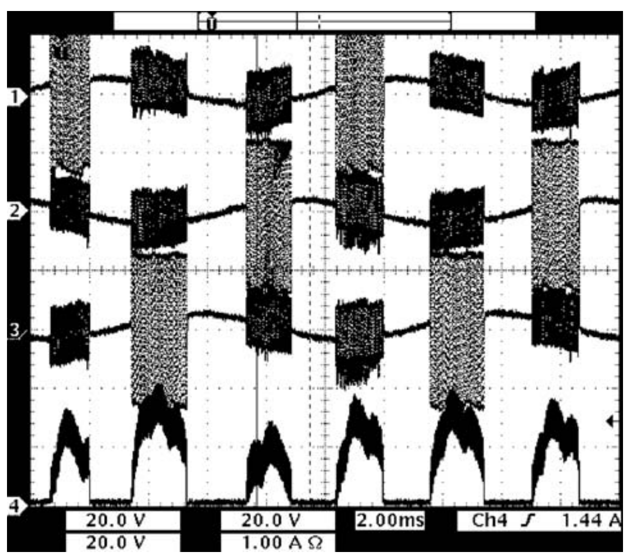

Fig. 8 Back emf CH1 – e_1, CH2 – e_2, CH3 – e_3 and star current CH4 – i_Z

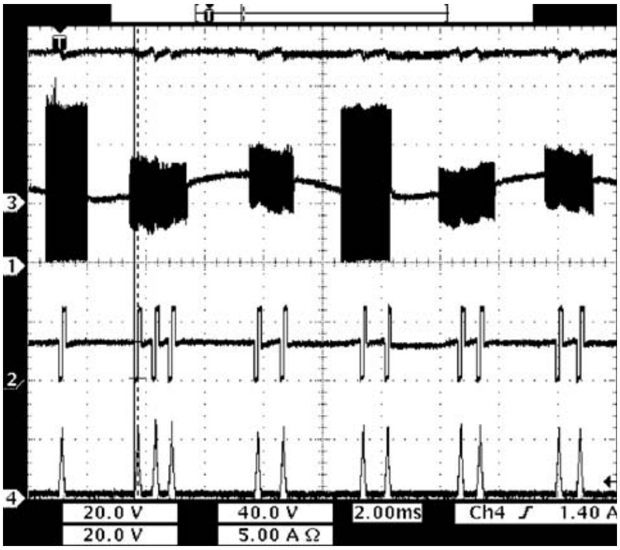

Fig. 9 Voltage on low side switch CH1 – u_{DS1}*, voltage on the top side switch (BUCK) CH2 –* u_{DS4}*, second DC-Link voltage CH3 –* u_{DC2}*, BUCK inductor current CH4 –* i_{L1}

windings. Figure 9 shows the voltage on the low side switch (BOOST converter) u_{DS1}, voltage on the high side switch (BUCK converter) u_{DS4}, second DC-Link voltage u_{DS2} and the inductor current i_{L1} which connect both DC-Links. The efficiency (3) for a converter with snubbers was measured at 64 % and the discussed solution at 83 % where P_{in} is the input power and P_{e} is the electrical PMSM power.

$$\eta = \frac{P_{\mathrm{in}}}{P_{\mathrm{e}}} \tag{3}$$

5 CONCLUSION

This paper presents a low cost unipolar converter with speed control for BLDC-PMSM drive. The converter is made of simple and inexpensive discrete elements which guaranties low production costs and robustness. Although it is low cost it fulfills the requirements for a simple application. It is also shown that the converter with speed control for BLDC-PMSM can be build by using simple circuits and that voltage on switching elements is under control without usage of snubber circuits.

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Niskocjenovni visokoučinkoviti jednopolarni pretvarač za sinkrone motore s permanentnim magnetima. U radu se opisuje jeftini jednopolarni učinski pretvarač za sinkrone motore s permanentnim magnetima (SMPM). Korištene su samo tri tranzistorske sklopke slično kao kod jednopolarnih elektronički komutiranih motora. Međutim, postignuta je znatno viša učinkovitost jer nisu bili potrebni prigušni krugovi. Umjesto disipacije u prigušnim krugovima energija se vraća u izvor preko silaznog pretvarača. Topologija pretvarača može se prikazati kao kombinacija višefaznog uzlaznog pretvarača i jednofaznog silaznog pretvarača, gdje namoti SMPM služe kao induktiviteti uzlaznog pretvarača. Upravljanje SMPM izvedeno je na osnovi signala iz ugrađenog Hallova senzora i razvijenog jeftinog sklopa za predobradbu njegova signala.

Ključne riječi: sinkroni motor s permanentnim magnetima, uzlazni pretvarač, silazni pretvarač

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