Sensorless Detection of Rotor Position of PMBL Motor at Stand Still

Roustiam Chakirov, Yuriy Vagapov, and Andreas Gaede

***Abstract* — The article presents a solution to detect rotor position at stand still condition for all types of permanent magnet brushless dc motors. The solution provides both secure and fast method for starting of the brushless motor, that is independent on the sensorless control scheme used. Nonlinearities found in standard three phase permanent magnet dc motor are used to derive the rotor position at stand still. The described solution assumes that there is availability of the neutral point of the three phase star motor windings.**

***Index Terms* — permanent magnet brushless dc motors, rotor position, sensorless control.**

I. Introduction

A permanent magnet brushless dc motor with trapezoidal flux distribution (BLDC) and a permanent magnet synchronous motor with sinusoidal flux distribution (PMSM) are used in a large number of industrial and automotive applications because of their high efficiency, compactness and excellent reliability. Main drawback of these systems, regardless whether block commutation or high sophisticated field oriented vector control used, is the necessity of having the actual rotor position information: only with this information the correct commutation commands and current control signals can be derived. However, sensor costs, installation expenditure and demands for additional space within the motor considerably influences the drive layout and noticeably increases the total system cost.

For this reasons, elimination of the rotor position sensing is regarded as goal of first order. This can be done by installing a sensorless control scheme of the permanent magnet BLDC motor. Different approaches of obtaining such a control scheme, depending of the motor design, flux distribution, commutation method, required system performance and cost targets has been published in [1], [4].

Manuscript received July 22, 2007.

Roustiam Chakirov is a professor in Control Systems and Automotive Technology with the Department of Electrical and Mechanical Engineering, Bonn-Rhein-Sieg University of Applied Science, 20 Grantham-Allee, Sankt Augustin, D-53757, Germany (phone: +49 (0)2241 865-398; fax: +49 (0)2241 865-8398; e-mail: roustiam.chakirov@fh-bonn-rhein-sieg.de).

Yuriy Vagapov is with the School of Science and Technology, North East Wales Institute of Higher Education, University of Wales, Plas Coch, Mold Road, Wrexham, LL11 2AW, UK (e-mail: y.vagapov@newi.ac.uk).

Andreas Gaede is with the School of Science and Technology, North East Wales Institute of Higher Education, University of Wales, Plas Coch, Mold Road, Wrexham, LL11 2AW, UK (e-mail: a.gaede@newi.ac.uk).

However, for all schemes the motor starting is the weak point of these drives: at stand still no information can be derived form the algorithms used at running motor. Some schemes, e.g. in computer hard disk drives, use open-loop control start techniques to speed up the drive to that point where the sensorless control scheme begins to work properly. Reliability of this starting procedure is usually improved by initialising the motor to a predetermined initial rotor position. A simple way to do so is to run the motor as stepper motor for half an excitation cycle and than to lock the rotor position by a constant stator holding current.

Some disadvantages of this method are:

- a very long time is needed, first to bring the shaft into the desired starting position, and second to damp the mechanical oscillations of the rotor;
- at the beginning of the excitation cycle the motor can rotate in the wrong direction, which is not allowed in some applications;
- some application even do not allow any rotor movement i.e. due to a holding torque.

Therefore it is preferred to know the rotor position before starting. For fast and reliable starting, an accuracy of ±30 electrical degrees of the rotor position detection proved to be sufficient. All known principles for determining the rotor position at stand still are based on special motor structures with e.g. magnetic, geometric asymmetries or position dependent eddy current paths [3].

II. Rotor Position Detection

In salient-pole motors the rotor asymmetry leads directly to differences in the magnetic reluctance values in the rotor direct axis (*d*-axis), which is the axis of permanent magnet flux, compared to the values found in the quadrature axis (*q*-axis), which is the axis perpendicular to *d*-axis. So measuring both values of the initial rotor position can be derived from the two measurements [2]. However the majority of permanent magnet drives are of non-salient nature, e.g. bread loaf or radial magnet design, where the values of L_d and L_q are nearly equal.

The rotor position detection technique proposed in this article uses a similar effect. It is caused by magnetic saturation in the stator laminations and can be found in almost every permanent magnet motor. The reason for this is that almost every electric motor design targets its cost minimum. This leads to high magnetic loading inside the motor, i.e. magnetic flux densities from 1.5T up to 1.8T in the stator tooth areas are common in order to achieve high drive efficiency and good utilisation of the motor materials. Flux densities of that level cause light up to middle saturation in the electromagnetic paths of the stator windings. Since the motor windings are equally distributed within the stator bore, the teeth belonging to one phase have different locations within in the stator bore relative to the teeth of the next phase. The amount of the saturation depends on the position of the rotor magnets relatively to the stator teeth looked at. Hence the degree of saturation of the teeth, which belongs to a phase, depends on the rotor position.

If we apply a current in a phase winding, this current produces a magnetic flux which adds to the flux of the permanent magnet. If the direction of the current generated flux points in the same direction as the rotor *d*-axis, the total flux increases which leads to a higher saturation level of that stator section; if, on the contrary, the directions of the stator magnet field points against the rotor magnet field, the total magnet flux density decreases and the magnetic paths of that stator section are unloaded.

Since the differential inductance of a phase winding depends on the saturation level of its electromagnetic path, the magnetic loading due to the rotor magnets in conjunction together with the loading due to the stator current leads to a rotor position and current dependant change of the differential phase inductance. These dependencies are the base to derive the required rotor position for motor start-up.

Overall goal of the proposed method is not the precise information of the rotor position. Since for both type of brushless permanent magnet motors, BLDC and PMSM, the start-up is done with rectangular current waveforms, i.e. block commutation, an angular resolution of only 60° is required. A further advantage in doing so when using PMSM-drives is a higher torque output at the same current peak level compared to a sinusoidal current waveform.

One approach in order to get information on the saturation level is to apply a voltage pulse and to measure at the end of the voltage pulse the amplitude of peak phase current. By comparing the current amplitudes of different voltage pulses the information on the rotor position can be estimated. The drawback of that solution is the necessity of the precise current measurement information, high noise sensitivity and a stiff voltage source when the phase currents are impressing.

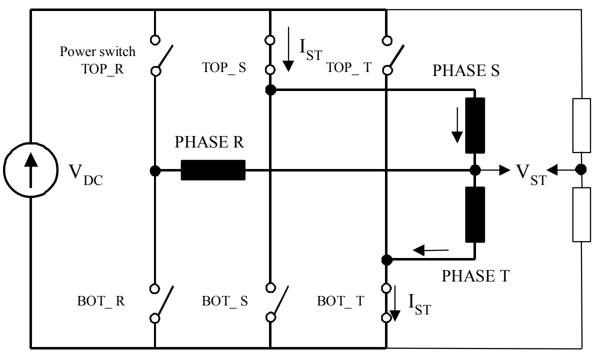

Fig. 1. Circuit schematic of the measurement bridge using a three-phase inverter as demultiplexer. Phase S and T are conducting.

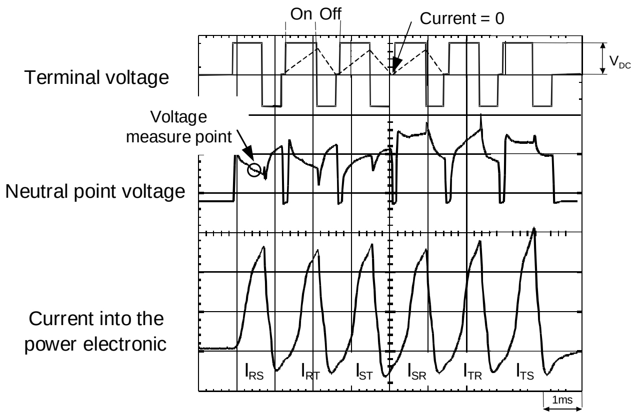

Fig. 2. Measured terminal voltages, neutral point voltages and input current waveforms of the power electronics during experimental rotor position detection

The approach proposed here only needs the information on the relative change of motor inductances and does not require knowledge of any motor parameter. The main idea of the approach is to use the motor as a part of a measuring bridge. As shown in Fig. 1, the motor is one half of the bridge, the other half is built by two additional resistors. The phases which are in the bridge are selected by the power switches of the motor electronics. For the measurement, the voltage input to the bridge is a voltage pulse generated by the power switches which select as well the motor phases; the output of the bridge is the voltage measured between the neutral point of the motor and the middle of the resistive divider.

Thus, when a voltage pulse is applied to the bridge a change in the inductances of the connected motor phases due to change of magnetic saturation has a direct effect on the output of the bridge, i.e. the voltage V_{ST}.

The voltage pulses on the inductive part of the bridge are generated by the switches of the motor power electronics. According to the six available switching states of the inverter six voltage pulses are applied to terminals labeled R, S, T. The time durations for the on- and off-times of the pulses are equal and constant during all measurements. The cycling of the voltage pulses are done in a fashion that minimum rotor movement will occur.

Possible dc-link voltage fluctuations during the measurement are compensated by using the measurement bridge principle. Great benefit of this voltage sensing method is that no current measurement is needed and that a much higher level of measurement sensitivity is received compared to current based methods.

III. EXPERIMENTAL IMPLEMENTATION

Fig. 2 shows the experimental waveforms of the neutral point voltage and current responses during the initial rotor position detection. For experimental verification the rotor position estimation scheme was tested with a three-phase automotive BLDC motor having twelve slots and eight poles rated for 12V voltage supply.

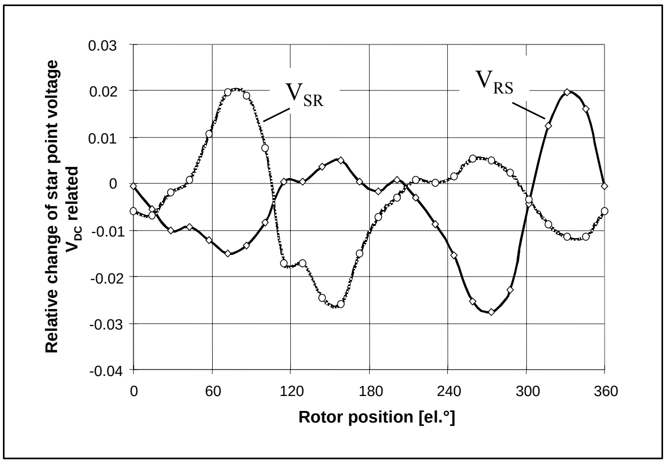

Fig. 3. Distribution of bridge output voltage as function of the rotor position V_{RS}; current flowing from phase R to phase S; V_{SR} current flowing from phase S to phase R.

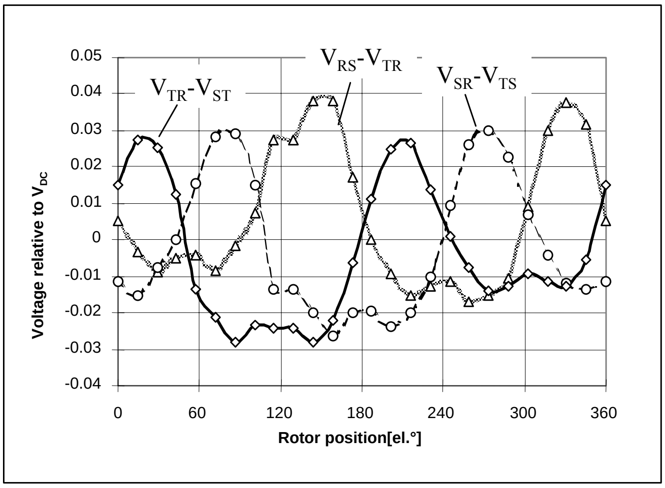

Fig. 4. Outputs of the equations system (1) relative to the rotor position.

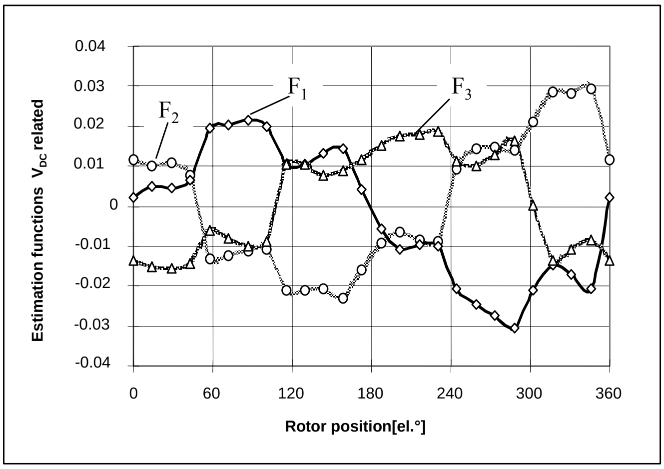

Fig. 5. Outputs of the estimation functions F_1 to F_3 relative to the rotor position

During measurements the voltage pulses have to meet the follow requirements:

- the amplitude of the phase current should be in the range of the nominal current to produce the highest possible change of saturation state in stator;
- the length of current pulses has to be as short as possible to avoid any rotor movement;
- the next current pulse should be started short after the previous current pulse is diminished to zero.

As can be seen in Fig. 3 the rotor position can not be derived directly from these waveforms. To get more information out of theses waveforms the following analysis functions have to be applied:

$$V_{RS} - V_{TR},\ V_{SR} - V_{TS},\ V_{TR} - V_{ST} \tag{1}$$

where V_{RS} is the bridge output voltage during the voltage pulses when current is fed from dc supply to the motor via phases R and S, while phase terminal R is connected to dc voltage and phase terminal S is connected to ground; all other voltages are derived accordingly. Distribution of these functions is showed in Fig. 4.

Fig. 4 shows that by applying some simple logical functions the rotor position can be estimated within 180 electrical degrees. These functions are shown in Table 1.

TABLE I
LOGICAL EQUATIONS FOR ROTOR POSITION ESTIMATION

Logical terms	Rotor position θ
$(V_{RS}$-V_{TR}>V_{ST}-$V_{TR})$&$(V_{RS}$-V_{TR}>V_{TR}-$V_{ST})$	120°~180° or 300°~360°
$(V_{SR}$-V_{TS}>V_{RS}-$V_{TR})$&$(V_{SR}$-V_{TS}>V_{TR}-$V_{ST})$	0°~60° or 180°~240°
$(V_{TR}$-V_{ST}>V_{RS}-$V_{TR})$&$(V_{TR}$-V_{ST}>V_{SR}-$V_{TS})$	60°~120° or 240°~300°

TABLE II
ROTOR POSITION DETECTION USING ESTIMATION FUNCTIONS

Sign of estimation functions			Sector code			Sector	Rotor position θ
F_1	F_2	F_3					
F_1>0	F_2<0	F_3>0	1	0	1	5	0°~60°
F_1>0	F_2<0	F_3<0	1	0	0	4	60°~120°
F_1>0	F_2>0	F_3<0	1	1	0	6	120°~180°
F_1<0	F_2>0	F_3<0	0	1	0	2	180°~240°
F_1<0	F_2>0	F_3>0	0	1	1	3	240°~300°
F_1<0	F_2<0	F_3>0	0	0	1	1	300°~360°

The result of this logical analysis is the detection of two 60° segments of which one corresponds to the actual rotor position. In order to detect the correct one of the two a second detection algorithm has to be applied. The estimation functions are:

$$\begin{aligned} F_1 &= \left(V_{RS} + V_{SR} + V_{ST} + V_{TS}\right) - \left(V_{RT} + V_{TR}\right) \cdot 2 \\ F_2 &= \left(V_{RS} + V_{SR} + V_{RT} + V_{TR}\right) - \left(V_{ST} + V_{TS}\right) \cdot 2 \\ F_3 &= \left(V_{ST} + V_{TS} + V_{RT} + V_{TR}\right) - \left(V_{RS} + V_{SR}\right) \cdot 2 \end{aligned} \tag{2}$$

Fig. 5 shows the outputs of the estimation functions F_1, F_2 and F_3 respectively to the rotor position.

These graphs are periodical functions with a period at 360 electrical degrees and with a phase difference of 120° between adjacent curves. Therefore these functions are interpreted as signals of a "virtual Hall effect sensor system" correspondent to a Hall effect sensor system in standard BLDC-drives. Table 2 shows some details of the detection. Just from the function polarities a rotor position resolution of 60 electrical degrees is obtained. These results are sufficient to start the motor in a way, how it is done in standard BLDC-drives with block commutation.

IV. Conclusion

In this article the authors propose a rotor position detection method at motor stand still condition. The only necessary measurement quantities are the neutral point voltage and some voltage pulses at the motor terminals. The time needed to detect the rotor position is less than 50ms. The proposed algorithm is simple, insensitive to measuring noise and can easily be implemented in BLDC drive control based on cost-effective 8-bits microcontroller with only minor extra costs.

References

[1] K. Tae-Hyung, and M. Ehsani, "Sensorless control of the BLDC motors from near-zero to high speeds," *IEEE Transactions on Power Electronics,* vol. 19, June 2004, pp. 1635 – 1645.

[2] U.-H. Rieder, M. Schroedl, and A. Ebner, "Sensorless control of an external rotor PMSM in the whole speed range including standstill using DC-link measurements only," *Proceedings of 35th IEEE Power Electronics Specialists Conference, PESC 04*, vol. 2, June 20-25, 2004, pp. 1280 – 1285.

[3] H. Takashima, M. Tomita, C. Zhiqian, M. Satoh, S. Doki, and S. Okuma, "Sensorless position and velocity control of cylindrical brushless DC motors at low speed using eddy current," *Proceedings of the IEEE Power Conversion Conference*, vol.3, April 2-5, 2002, pp. 1300 – 1303.

[4] P.B. Schmidt, M.L. Gasperi, G. Ray, and A.H. Wijenayake, "Initial rotor angle detection of a nonsalient pole permanent magnet synchronous machine," *Proceedings of the IEEE Industry Applications Conference, the 32nd IAS Annual Meeting, IAS 97*, vol. 1, October 5-9, 1997, pp. 459 – 463.