

Investigation of Self-sensing Rotor Position Estimation Methods for Synchronous Homopolar Motor in Traction Applications

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Abstract—This paper investigates two methods of self-sensing rotor position estimation based on signal injection for a homopolar synchronous motor. The magnetic anisotropy of the machine can be utilized for rotor position estimation, which can exclude a position encoder from the system in order to increase reliability of the drive. The stator response observer was tested and the field response observer was proposed and tested. The experimental results show good self-sensing control capability of this type of electrical machine. The proposed field response observer provides accurate results which are practically independent from the load on the motor shaft. A sensorless control system was implemented in a traction drive of a pure electric city bus, and uses both self-sensing and back-EMF rotor position observers for operation over the entire speed range.

Keywords—*Synchronous homopolar motor, Traction drive, Self-sensing control, Position estimation, Electric vehicle*

I. INTRODUCTION

One of the challenges of modern electric drives is sensorless control, which increases the reliability of the drive by excluding a position or speed sensor from the system. For traction drives, this ability is in high demand; however, the necessity of the torque control, even at zero speed, restricts the use of back-EMF observers which are very popular in standard industrial applications. The problem of zero and low speeds can be solved for the motors that have an observable magnetic anisotropy through self-sensing encoderless control. These systems are already implemented for permanent magnet synchronous machine [1], synchronous reluctance machine [2], permanent magnet assisted synchronous reluctance machine, switched-reluctance machine [3], doubly fed induction machine [4] and synchronous DC-excited machine.

The DC-excited machine is more attractive for self-sensing control because of its additional field winding that can be used as an extra measurement channel that provides information about current rotor position; moreover, the motor itself can be considered to be a rotary electrical transformer. The main disadvantage of the DC-excited machine for use in traction applications is the presence of a brushed contact that is needed to excite the motor.

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A Synchronous homopolar machine is another type of brushless synchronous machine, mostly used in aerospace and marine applications as a motor [5-7] and/or an alternator [8-10]. The magnetic topology of this machine allows its consideration as the DC-excited machine in terms of equations and control. This motor was already used for traction [7] and has some major advantages such as small losses in the rotor, absence of brushed contact, regulated flux for operation in a wide speed range with constant power, and magnetic anisotropy for self-sensing control, including the ability to operate as a rotary electrical transformer. This paper investigates the self-sensing capability of this motor by means of two different rotor position observers.

II. DESIGN AND MATHEMATICAL DESCRIPTION OF SYNCHRONOUS HOMOPOLAR MOTOR

Currently, there are several successful applications of the synchronous homopolar motor in traction of various rated powers, and the control principles are the same. The considered methods for self-sensing control and rotor position estimations were implemented using a 120 kW motor of a pure electric city bus. The design of the motor is shown in Fig. 1. The stator is slotless with distributed stator winding and the excitation winding is of buried type.

The equations of the machine [5] are the same as for synchronous DC-excited motor.

$$\left. \begin{aligned} v_d &= i_d R_s + \frac{d\psi_d}{dt} - \psi_q \omega, \\ v_q &= i_q R_s + \frac{d\psi_q}{dt} + \psi_d \omega, \\ v_f &= i_f R_f + \frac{d\psi_f}{dt}. \end{aligned} \right\} \quad (1)$$

Flux linkages are defined as follows; however, all inductances are non-linear and are affected by the flowing currents:

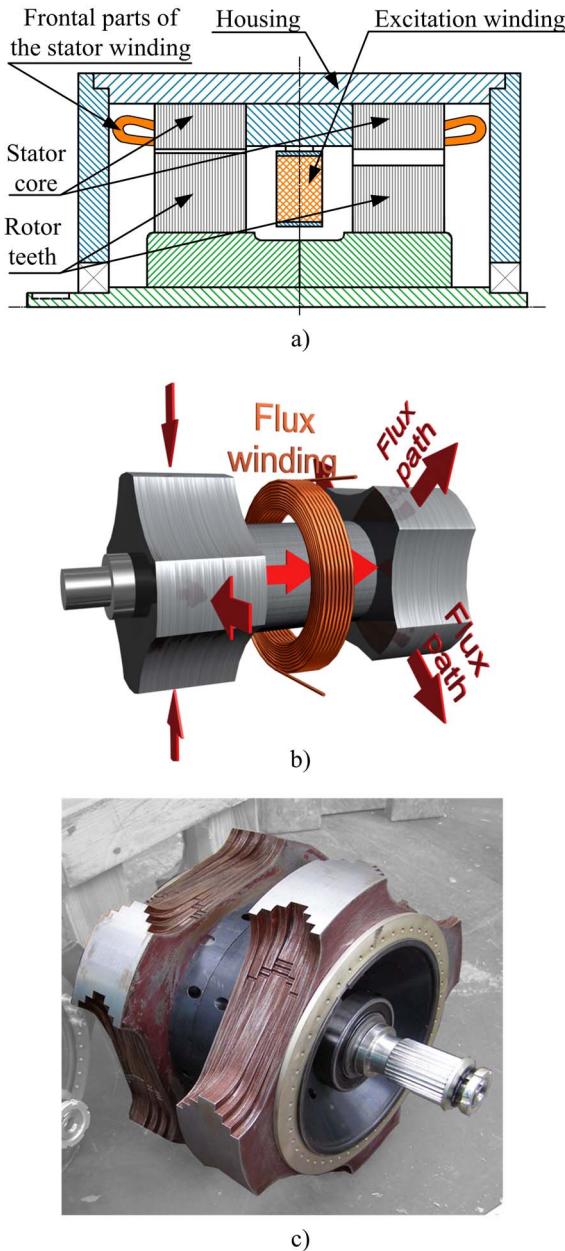


Fig. 1. Homopolar motor: a — design with buried excitation winding; b — simplified explanation of rotor design, c — rotor of a real motor.

TABLE I. MAIN PARAMETERS OF THE SYNCHRONOUS HOMOPOLAR MACHINE

Parameter	Value	Units
Rated power	120	kW
Rated phase-to-phase voltage	400	V
Rated current	500	A
Rated speed	1500	rpm
Rated excitation current	22	A
Maximum speed	6000	rpm
Pole pairs	4	-
Efficiency in the rated point	94	%

$$\left. \begin{aligned} \psi_d &= L_d \cdot i_d + L_m \cdot i_f; \\ \psi_q &= L_q \cdot i_q; \\ \psi_f &= L_m \cdot i_d + L_f \cdot i_f, \end{aligned} \right\} \quad (2)$$

where:

v_d , v_q and v_f represent the stator d and q axes voltages and the voltage of the field winding, respectively;

R_s and R_f represent the stator and field winding resistance, respectively;

ω represents the electrical speed;

ψ_d , ψ_q and ψ_f represent the flux linkages of the stator and field windings;

L_d , L_q , L_f and L_m represent the stator d -axis, q -axis, field winding and mutual inductances, respectively.

Torque has two components: one from the excitation current and quadrature stator current component, and the other the reluctance torque:

$$T = \frac{3}{2} p_p (L_m i_f i_q + (L_d - L_q) i_d i_q), \quad (3)$$

where p_p is the number of pole pairs. The motor has a higher inductance for the d -axis. Its main parameters are presented in Table I.

III. HIGH-FREQUENCY INJECTION METHODS FOR ROTOR POSITION ESTIMATION

There are two well-known general methods for sensorless rotor position estimation. The first one is based on back-EMF estimation, while the second utilizes the magnetic anisotropy of the machine.

The Back-EMF method works well at high and medium speeds; however, at slow or zero speed, the value of back-EMF becomes small or even zero. Thus, with a decrease in the motor speed, the accuracy of position estimation reduces and the rotor position can't be estimated at all at zero speed.

For zero speed, the self-sensing position estimation can be used if the motor has sufficient magnetic anisotropy. This homopolar synchronous machine has a d -axis inductance higher than the q -axis inductance; thus the injection of high-frequency voltage signal into stator windings results in the reflection in the stator currents, which depends on the position of d and q axes.

The estimation of the rotor position requires at least one injection cycle; therefore, this method is applicable only at low speeds. At higher speeds, the deviation of the rotor angular position can be considerable during a single position estimation (or high-frequency injection period); hence, with an increase in the speed, the control system should be switched to the back-EMF estimation method. This switching should be done as soon as possible, because any injection brings undesirable

impact on the characteristics of the drive due to some increase in the currents, acoustic noise and torque pulsation.

The injection methods can inject current or voltage. Voltage injection is most commonly used and, in turn, is split into injection of pulsating carrier signal [11] and injection of rotating signal [1, 11]. The injection frequency lies between 300 and 1000 Hz and the use of PWM switching sequence for rotor position tracking is considered in [11].

Unlike permanent magnet motors considered in [1-3], homopolar motor has additional sensing ability based on the magnetic coupling between excitation and stator windings. This coupling helps realise a self-sensing rotor position estimation which is independent of magnetic anisotropy [4].

Fig. 2 shows the control structure that was used to investigate both rotor position estimators, which are the stator response observer and the field response observer. The control strategy has no position feedback and allows the implementation of any rotating current vector together with signal injection.

IV. STATOR RESPONSE OBSERVER

The implemented stator response observer is known from [1, 11]; therefore, its description is skipped, while experimental results for the homopolar synchronous motor are provided to show that this method is applicable for such electrical machines.

Three experiments were conducted with different conditions. At first, the current reference was set to zero to investigate the rotor position estimation under idle load. The experiment was conducted for three different fixed rotor angular positions of 300, 240, and 60 electrical degrees and an

injection frequency of 250 Hz. The response in the phase currents on the high-frequency injection is shown in Fig. 3. The deviation of the high-frequency component of the phase current indicates that the phase inductance changes more than three times. This gives enough information for rotor position estimation.

During the second experiment, the current reference was set to zero; however, this time the motor under test was rotated by another motor at 170 rpm. The position is observed with relatively good accuracy (see Fig. 3d). It is not possible to distinguish the exact direction of the d-axis by means of this method; thus, the position estimation is doubled to the actual value.

The last experiment was performed with the stator current reference of 60 A; the speed reference was 120 rpm. Under these conditions, the motor rotates in an open loop. The increase of the phase current puts the machine into saturation, which results in much poor accuracy of position estimation (see Fig. 3e). Though the accuracy is reduced and only six positions are observable, the resolution itself is the same as that for an ordinary Hall-effect position sensor. Thus, this method is acceptable for homopolar synchronous motors.

V. FIELD RESPONSE OBSERVER

The accuracy of the considered stator response observer suffers from the saturation of the motor due to high currents under load. This method utilizes deviation in stator inductances, while homopolar synchronous motor has an extra measurement channel — excitation winding. According to (2), the change of the d-axis stator current also results in change of the flux linkage of the excitation winding; thus, the injection into stator is observable in the field current.

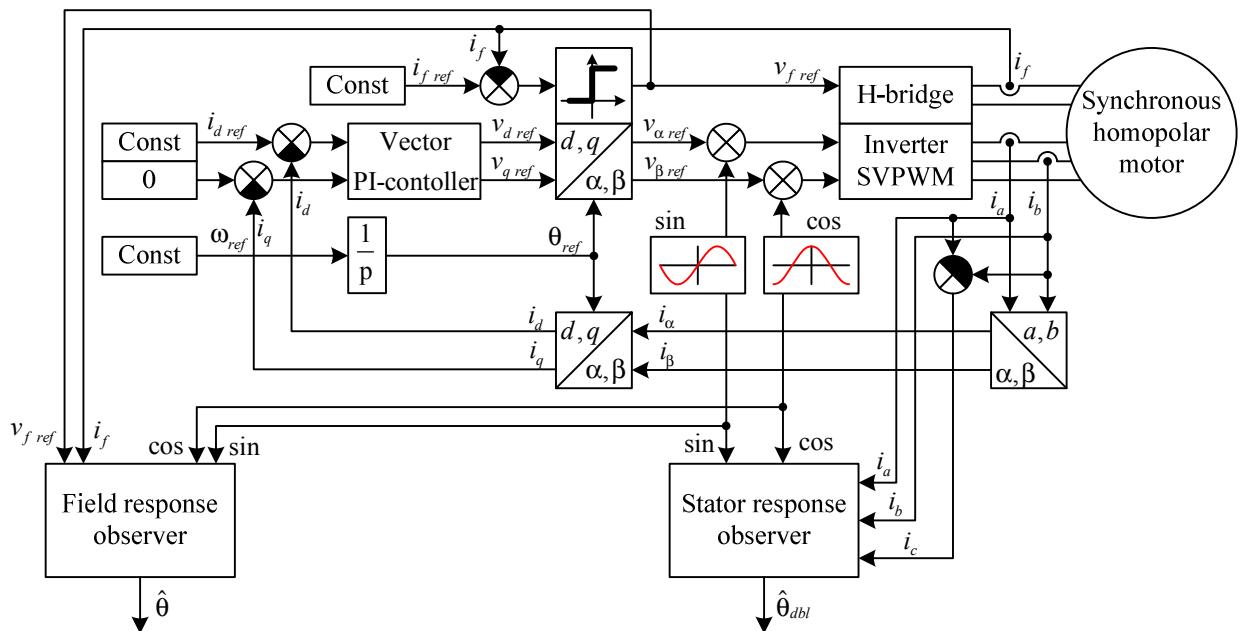


Fig. 2. Control structure for position estimation test.

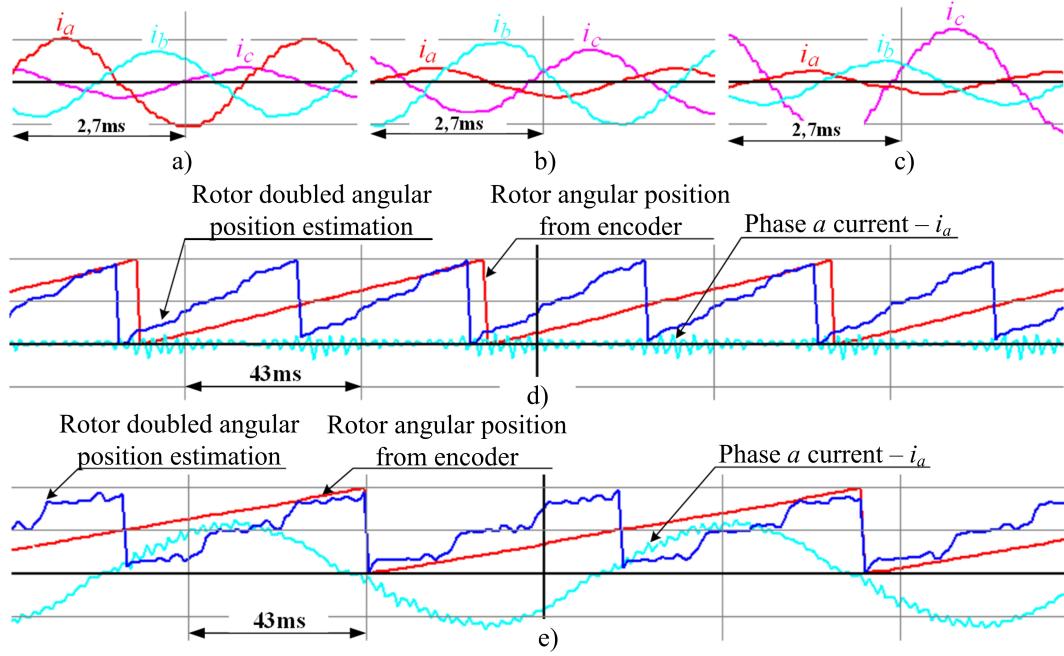


Fig. 3. Position estimation using high-frequency injection method with stator response observer: a — three phase currents for 300 electrical degree position; b — three phase currents for 240 electrical degree position; c — three phase currents for 60 electrical degree position; d — rotor angle estimation for zero stator current reference; e — rotor angle estimation for 60 A stator current reference.

The excitation winding is under control of a hysteresis current controller. If the field current is below the referenced value, the DC link voltage is applied to the winding; otherwise, the winding is shorted, equivalent to a zero voltage applied. The operation of the field current controller simultaneously with high-frequency injection into stator windings for two opposite rotor angles of 0 and 180 degrees is presented in Fig. 4. The response in the field current has the same magnitude for both experiments, but the phase is different.

The current in the excitation winding is affected by the hysteresis controller, which brings disturbance into the shape of the current. Such a disturbance can be excluded from the signal by means of a disturbance observer that should predict the behaviour of the current in the winding according to the switching sequence of the hysteresis controller.

The block diagram of the observer is shown in Fig. 5. It contains an integrator that represents the inductance of the field winding L_f . The applied voltage is integrated into the estimated current of the field winding \hat{i}_f that causes a voltage drop in the estimated resistance of the winding \hat{R}_f . Due to significant temperature deviation, the resistance of the excitation winding changes during the operation; and the difference between the estimated and measured field current is used to correct the value of the winding resistance by means of a resistance observer comprising an integrator with very small gain K_{res} . When all the parameters of the model are correct, the difference between the measured and estimated currents provides pure response $i_{f,inj}$ from the injected signal.

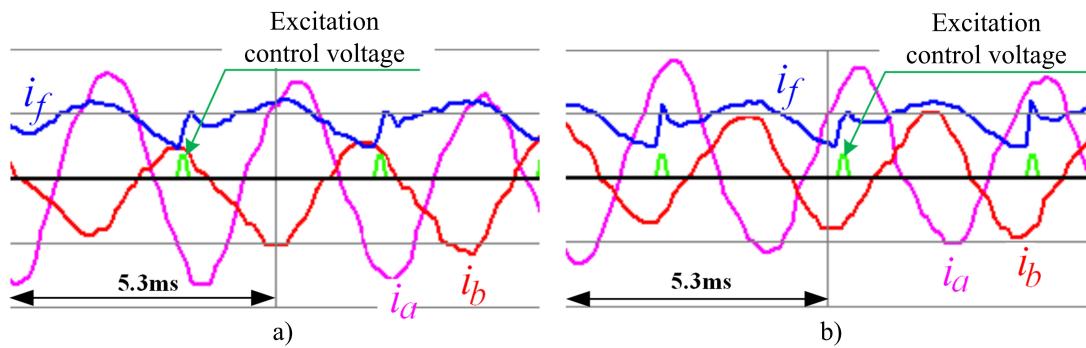


Fig. 4. Current response in the excitation winding of the synchronous homopolar motor: a — rotor position is 0 electrical degree; b — rotor position is 180 electrical degrees.

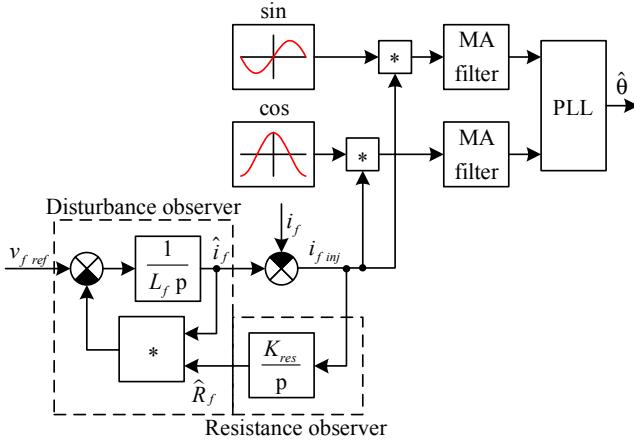


Fig. 5. Block diagram of a field response observer.

The response signal has a different phase that is dependent on the rotor angular position. To determine the phase of the signal, the signal is multiplied by sine and cosine of the injected signal. The moving average filters (MA filter) have a window size equal to the period of the injection and provide sine and cosine components of the actual rotor position. These signals are processed with PLL-based position estimator, which operates as a filter that removes noises from the extracted signals.

Fig. 6 illustrates the start up of the motor with the proposed position estimator. The accuracy of the position estimation was checked by means of the Hall-effect position sensor. Its signal is interpolated, by software, from some minimal speed. The error of estimation is small and the result is sufficiently accurate for operation of a field-oriented control system.

VI. CONCLUSIONS

A Synchronous homopolar motor is suitable for sensorless operation over its entire speed range, including zero speed. This ability is necessary for the traction drives, the reliability of which is currently limited due to the presence of the rotor position encoder needed for operation at low speeds. An extra information channel provided by the excitation winding adds an advantage to this motor in comparison to permanent magnet synchronous machines, and increases the accuracy of position estimation.

The proposed observer was tested on the motor of the pure electric city bus. It passed the tests in all speed ranges. Together with the back-EMF estimator that switches on at medium and high speeds, the control system operates in the sensorless mode from zero to maximum speed.

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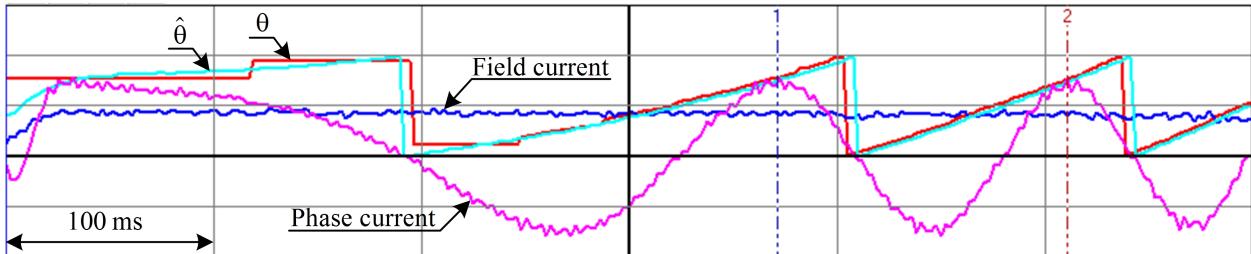


Fig. 6. Rotor angular position estimation during start up of the motor with field response observer (phase current 100 A per division; field current 5 A per division).