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Improving the Accuracy of Switched Reluctance Motor Sensorless Rotor Position Estimation

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Abstract: This study presents developing accurate sensorless SRM rotor position estimation in start-up mode. The accuracy of rotor position estimation is improved by choosing rational parameters of probing pulses.

Key words: Switched reluctance motor, sensorless control, probing pulse, estimation, accuracy

INTRODUCTION

As a rule, modern drive systems are built on the basis of induction electric machines. However, in recent years other types of electric motors become increasingly popular. For example, a large proportion of recent publications is devoted to the study of Switched Reluctance electric Machines (SRM) which can be called one of the most promising types of electromechanical energy converters.

For effective use of SRM it is necessary to control phase excitation current in accordance with rotor position. Typically, this is done using physical rotor position sensor fixed on the machine shaft (optoelectronic sensors, Hall-effect sensors, etc.). For systems intended to operate in harsh environments the position sensor may become a limiting factor. Meanwhile, it is possible to determine rotor position indirectly using dependence of phase flux of the phase current and rotor position $\psi = f(i, \theta)$ (Acarnley *et al*., 1985). Control systems based on the indirect rotor position estimation are called sensorless systems.

Currently, researchers published many works on synthesis and study of sensorless control of SRM. Typically, the methods of indirect rotor position estimation are classified on methods of active phase measurement and methods based on passive phase measurement. Using the methods of the first group limits the active phase current control and hence the SRM torque control. Among the methods of second group there are methods, based on short voltage pulses (probing pulses) application (Mvungi, 2007). In this case, it is possible to use effective algorithms of active phase control. However, it is necessary to consider the impact of probing current on energy effectiveness indexes and torque curve when the probing current is commensurate with the active phase current. On the other hand, if the sensing current is small it is necessary to protect usefull signal from noise.

Another approach allows to allocate methods based on the use of markers and methods based on look-up tables which require not only a large amount of memory of the microprocessor control systems but also time-consuming to determine the look-up table data. In addition, look-up tables do not take into account the differences in the characteristics of the phases which may arise as a result of the inaccuracies during SRM manufacturing process. Methods based on the use of markers are generally limited to the rotation frequency or excitation current control.

ACCURATE SENSORLESS ROTOR POSITION ESTIMATION

SRM sensorless control enhances application of the switched reluctance drive systems in the most adverse operating conditions: high temperature, chemically aggressive environment, intense radiation exposure to the motor. In this case, of paramount importance the fact of the possibility of SRM operation without physical rotor position sensor. According to the level of reliability and durability sensorless switched reluctance drive exceeds its nearest competitors. The situation is different in the field of general industrial electric drive, when except reliability and durability other indicators are important (energy efficiency, electromagnetic torque ripple and the noise level).

Considering the influence of sensorless control on noise and vibration level it is necessary to specify that the greatest impact on these indicators will provide inaccurate

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indirect rotor position estimation. Using position sensor control system receives information about the rotor position with a relatively low latency due to the speed of CPU. In this case, the error of rotor position estimation depends on the accuracy of position sensor calibration. When sensorless control is used the accuracy of look-up table, the large amount of computation required to determine the value of θ and the accuracy of measurement equipment impact on rotor position estimation accuracy. All this is the cause of a time-varying error of estimating rotor position and as a result changing the actual angles of opening and closing the semiconductor switches of the converter. In this case, the magnetic system is in a state of artificial asymmetry as during dwell angle phase flux linkage take on different values. Thus, the main difference of SRM sensorless control will be the artificial phase excitation unbalance which serves as a source of additional noise and vibration (Krishnan, 2001; Nasirian *et al*., 2013).

The reduction of sensorless switched reluctance motor noise level and improving of its energy efficiency may be achieved by accuracy increasing of indirect rotor position estimation. As investigates was accepted the algorithm of sensorless control described by Tchavychalov. Algorithm based on the use of sensing pulses and a marker. Amplitude of sensing pulse current in unaligned rotor position (180 electrical degrees) is used as a marker. Switching of phases occurs after marker, i.e. when control system registers the current amplitude of the sensing pulse which is less than the current amplitude of the previous sensing pulse. Picture of the phase current is shown in Fig. 1.

Since, the actuation of the marker until the rotor position of 180 electric degrees with respect to the electrical probed phase is impossible in principle, the accuracy of the rotor position estimation is determined:

$$Q = \theta_m - 180$$

where, θ_m rotor position with respect to the electrical probed phase in which the last probing current amplitude before the marker actuating is fixed.

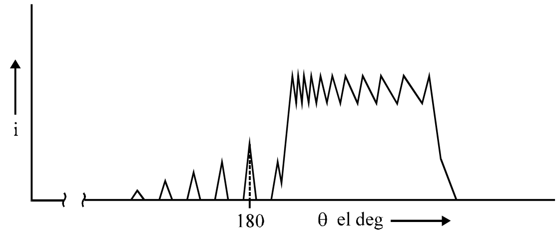

Fig. 1: The curve of phase current of sensorless SRM

As a means of solving the problem of increasing the accuracy of the indirect rotor position estimation is considered the choice of rational parameters of the probing pulses. In as much as for determining rotor position is only the relative value of the probe pulse current amplitude is used prescribing the accuracy of rotor position estimation Q_{ref} (electrical degrees) to achieve better energy efficiency and noise level characteristics can be changed the period of probing pulses P and the duty ratio D which is defined as:

$$D = \frac{W}{P}$$

where, W time period in which the power converter switches are opened sec. When selecting the duty ratio should be excluded situation in which the value of the probing pulse current is too small to fix it by means of measurements. Based on this, it is rational to set W = Wmin which is dependent on the capabilities of measuring equipment and SRM parameters.

Assuming that the motion of the rotor within the electrical switching cycle is uniformly accelerated and extrapolating the value of the angular acceleration ε on the next electric cycle for the angle of rotation of the rotor can be written:

$$\theta = \frac{N_r \cdot 180}{\pi}\left(\omega_0 \cdot t + \frac{\varepsilon}{2} \cdot t^2\right)$$

Where:

t = Time (sec)

ω_0 = Rotor rotation frequency in the beginning of the electric cycle (sec^{-1})

Angular rotation of the rotor within one electrical cycle in a single-pulse mode of switching is defined as:

$$\Delta\theta = \frac{360}{N_{ph}}$$

where, N_{ph} SRM number of phases. The time of one electric cycle is defined as:

$$\Delta t = \frac{-\omega_0 + \sqrt{\omega_0^2 + 2 \cdot \frac{\pi}{180 \cdot N_r} \cdot \Delta\theta \cdot \varepsilon}}{\varepsilon}$$

Rotation frequency in the end of electric cycle:

$$\omega_f = \omega_0 + \Delta t \cdot \varepsilon$$

Assuming that the rotation frequency changes slightly in the period between the probing pulses from Fig. 2 for a period of probing pulses can be written:

$$P = \frac{2 \cdot \pi \cdot Q_{ref}}{3 \cdot 180 \cdot N_r \cdot \omega_f}$$

Given that the probing phase is in the field of generator mode, the maximum duty ratio $D_{max}<0.5$. for maximum rotor rotation frequency at which the constraint $Q = Q_{ref}$ is valid, we can write:

$$\omega_{ref\ max} = \frac{2 \cdot \pi \cdot Q_{ref} \cdot D_{max}}{3 \cdot 180 \cdot N_r \cdot W_{min}}$$

To verify the theoretical propositions the following mathematical model of SRM is used:

$$\frac{di_1}{dt} = \frac{1}{L_d(i_1, \theta)} \cdot \left(u_1 - i_1 \cdot R - \omega \cdot \frac{\partial \psi(i_1, \theta)}{\partial \theta} \right),$$

$$\frac{di_2}{dt} = \frac{1}{L_d(i_2, \theta)} \cdot \left(u_2 - i_2 \cdot R - \omega \cdot \frac{\partial \psi(i_2, \theta)}{\partial \theta} \right),$$

$$\frac{di_3}{dt} = \frac{1}{L_d(i_3, \theta)} \cdot \left(u_3 - i_3 \cdot R - \omega \cdot \frac{\partial \psi(i_3, \theta)}{\partial \theta} \right),$$

$$\frac{d\omega}{dt} = \frac{1}{J_{np}} \cdot \left(\sum_{m=1}^{3} T_m(i_m, \theta) - T_L \right),$$

$$\frac{d\theta}{dt} = \omega \cdot \frac{180 \cdot N_r}{\pi}$$

Where:

i_m = mth phase current (A)
$L_d(i_m, \theta)$ = Incremental inductance (H)
u_m = mth phase voltage (V)
ω = Rotor speed (sec)
ψ = Phase flux linkage (Wb)
J = Equivalent moment of inertia (kg·m^2)
T_m = Torque produced by the current of mth phase (Nm)
T_L = Load torque (Nm)

Computer simulation of sensorless control is done on the example of the 3-phase SRM configuration 12/14 (12 tooth on stator, 14 tooth on rotor).

On the computer model sensorless start-up in a course in ideal current limit mode was carried (current limit 10 A, DC link voltage 300 V, p = 500·10^{-6} sec, D = 10%). On Fig. 3, curves of phase currents and rotor speed are shown.

For the procedure of sensorless start-up dependence of rotor position estimation inaccuracy from time is shown in Fig. 4.

When considering Fig. 3 and 4 can be seen that the inaccuracy of the rotor position estimation increases with the rotor speed.

To decrease the inaccuracy of the rotor position estimation, described findings were incorporated into the

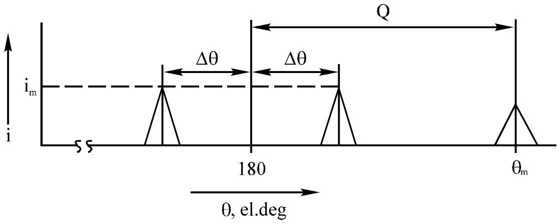

Fig. 2: The case of maximum sensorless rotor position estimation inaccuracy

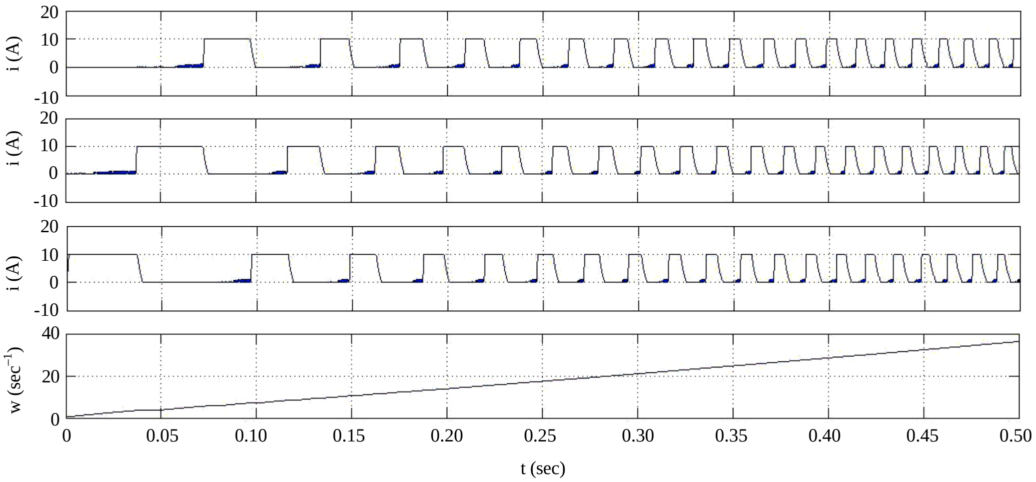

Fig. 3: The curves of phase current and rotor speed of sensorless SRM with constant D = const and P = const

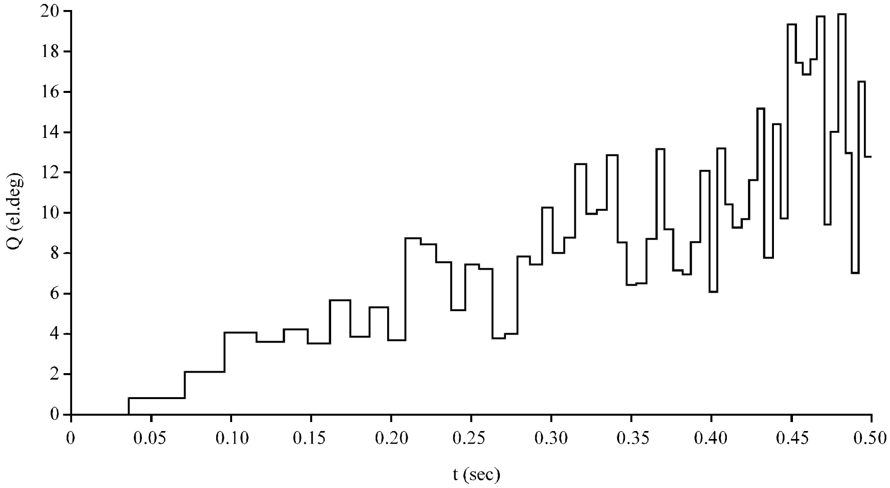

Fig. 4: SRM sensorless rotor position estimation inaccuracy while D = const and P = const

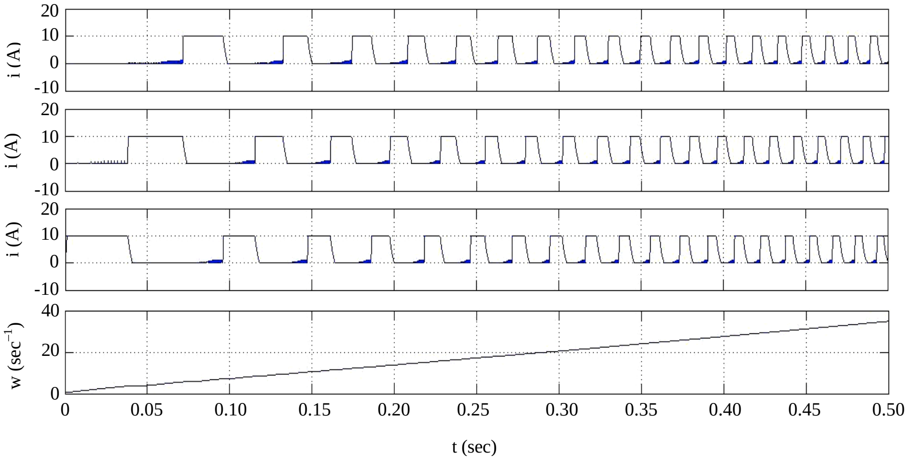

Fig. 5: Curves of phase current and rotor speed of sensorless SRM with constant D = var and P = var

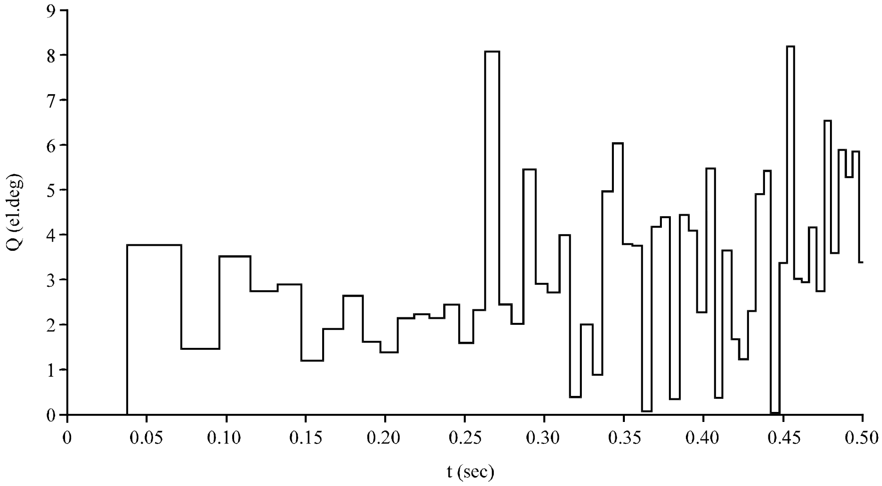

Fig. 6: SRM sensorless rotor position estimation inaccuracy while D = var and P = var

Computer Model. When $D_{max} = 0.3$, $W_{min} = 45{\cdot}10^{-6}$ sec and $Q_{ref} = 3$ electrical degrees dependencies of the phase currents and the rotor speed from time (Fig. 5) and the inaccuracy of the rotor position estimation from time (Fig. 6) were obtained.

Figure 6 shows that for the first commutation cycles the value of the inaccuracy of the rotor position estimation slightly exceed Q_{ref}. This is due to inaccurate calculation of the angular acceleration as well as the fact that during the P changing rotor speed $d\omega/dt \neq 0$. When these values Q_{ref}, D_{max} and W_{min} maximum speed of the rotor ω_{max} is:

$$\omega_{max} = \frac{2 \cdot \pi \cdot 3 \cdot 0.3}{3 \cdot 180 \cdot 12 \cdot 45 \cdot 10^{-6}} = 19.4 \text{ sec}^{-1}$$

From Fig. 6, it is seen that when $t > 0.25$ sec the condition $Q > Q_{ref}$ is not performed because $\omega > \omega_{max}$.

CONCLUSION

Thus, changing the P and D at a constant value $W = W_{min}$ it is possible not only improve the accuracy of determining the rotor position in sensorless startup mode but also to determine the maximum speed of the rotor whereby the rotor position estimation inaccuracy does not exceed a predetermined value. In addition, given that being probed phase operates in generator mode, described measures will help to improve the energy efficiency of the electric drive.

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