Letters

Permanent Magnet Flux Online Estimation Based on Zero-Voltage Vector Injection Method

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***Abstract*—In this paper, a simple and accurate method is proposed for online estimation of the rotor permanent magnet (PM) flux linkage for surface mounted PM synchronous machines. By advantageously utilizing an injected zero-voltage vector, the effects of inductance in estimating the PM flux linkage is eliminated. The inverter voltage error and phase resistive voltage drop effects are minimized by repeating the test at different speeds. Therefore, as a result, only the voltage commands are needed for PM flux linkage estimation, resulting in great simplicity. Filtering the current ripple caused by the zero-voltage vector injection is not necessary. The proposed method can be used with sensored or sensorless field-oriented control strategies. The experimental results have shown a good accuracy of the proposed new method.**

***Index Terms*—Permanent magnet (PM) flux linkage estimation, permanent magnet synchronous machines (PMSM), zero-voltage injection.**

I. Introduction

BENEFITED from the high torque density and high efficiency, permanent magnet synchronous machines (PMSMs) are increasingly employed in different industrial applications [1]. In most of the PMSM drive systems, machine parameters such as the stator phase inductance and the rotor permanent magnet (PM) flux linkage are considered as constants. Moreover, these machine parameters are usually measured offline using additional instrumentation. To measure the rotor PM flux linkage, it is often needed to run the PMSM as a generator with stator phases open circuited. The measured terminal voltage and speed are used to calculate the rotor PM flux linkage value. This requires controlling the load machine to run into a constant speed and voltage measurement is needed. In practice, this is not a convenient approach and the PM flux linkage may change due to, e.g., temperature rise [2], [3].

Rotor PM flux linkage may be involved in some control strategies for PMSM, such as rotor position estimation [4]; inductance online measurement [5]. The accuracy of the used PM flux linkage value may affect these estimation accuracies and the drive performance consequently [3], [5]. In additional, online estimation of the PM flux linkage may serve as condition monitoring for potential fault detection and necessary precautions may then be taken in time.

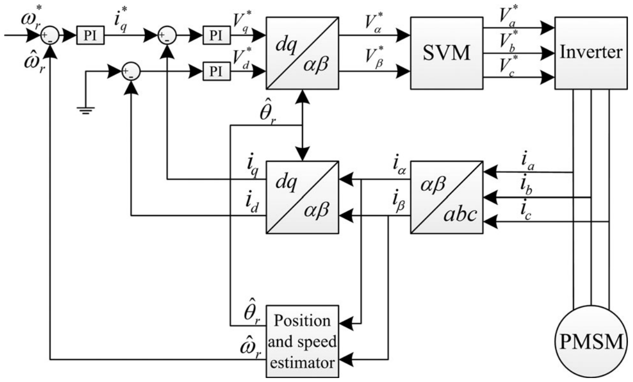

Fig. 1. Sensorless FOC system for SMPMSM.

In this paper, a simple and accurate method is proposed for PM flux linkage online estimation by using a zero-voltage vector injection scheme. The PM flux linkage is directly estimated by the average value of the voltage commands determined by the field-oriented control (FOC) current loop PI controllers at different speeds. The calculation does not involve the measured current information and no machine parameters are needed when the drive works under no-load or constant load conditions. The inverter voltage error effects are minimized and compensation of the inverter voltage error is not required. This proposed estimation method can be used in both sensored and sensorless drive systems. For both the FOC and PM flux linkage estimation, filtering the current ripple caused by zero-voltage vector injection is not necessary.

II. Control Fundamentals for PMSM

The voltage equations of the PMSM represented in the rotor *dq*-reference frame are well known, as

$$\begin{cases} v_d = Ri_d + L_d \dfrac{d}{dt} i_d - \omega_r L_q i_q \\ v_q = Ri_q + L_q \dfrac{d}{dt} i_q + \omega_r L_d i_d + \omega_r \lambda_{\mathrm{mpm}} \end{cases} \tag{1}$$

where v_d, v_q, i_d, i_q, L_d, L_q are the stator voltages, currents, and inductances in the *dq*-reference frame, respectively; R is the stator phase resistance, ω_r is the rotor speed, and λ_{mpm} is the peak value of the rotor PM flux linkage.

The proposed PM flux linkage estimation method is based on the classical FOC topology as shown in Fig. 1. In the FOC

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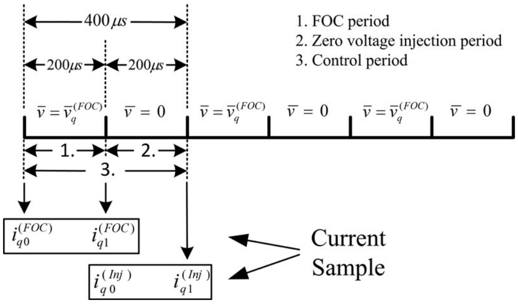

Fig. 2. Zero-voltage injection scheme.

system, the control is realized in the rotating *dq*-reference frame. The rotor position information is needed for transferring measured *abc*-currents to the *dq*-current components and converting *dq*-voltage commands to the $\alpha\beta$-voltage commands. The rotor position can be either obtained from a shaft encoder or from an estimator (sensorless).

III. ZERO-VOLTAGE INJECTION FOR PM FLUX LINKAGE ESTIMATION

The *q*-axis voltage equation in (1) indicates that the rotor PM flux linkage may be calculated by using the *q*-axis phase voltage. In most drive systems, there are no voltage sensors. The available voltage information is the voltage command only. These exists, e.g., inverter voltage error that brings voltage difference between the voltage command and real machine terminal voltage. Therefore, it is important to know or compensate the inverter voltage error when applying the voltage equation directly for rotor PM flux linkage estimation [6]. In the meantime, the output voltage is realized by pulse width modulation (PWM). Even when the drive is controlled in steady state, the current is not constant and there will be voltage loss on the inductance, which has to be taken into account and this requires the machine inductance to be known. Inverter nonlinear voltage error has a nonlinear behavior and the machine inductance may change due to saturation. In addition, when using the voltage equation for PM flux linkage estimation directly, current measurement error may also affect the estimation accuracy. Therefore, it will be an advantage that the PM flux linkage estimation may be accomplished without the need to know the inverter voltage error, the inductance value and it should be insensitive to current measurement errors. Without involving the inductance makes it also possible that the estimated PM flux linkage may be further used for online inductance estimation, e.g., [5]. To serve this purpose, additional zero-voltage vector switching periods are inserted between the PWM periods commanded by the FOC PI controllers, as shown in Fig. 2. The current in the $\alpha\beta$-reference frame can be measured at the beginning of each switching period, and then, are transferred to the *dq*-reference frame. The current variations during both the FOC period and the zero-voltage vector injection period may then be obtained.

In the traditional space-vector modulation algorithm, zero-voltage command will require to generate 50% duty cycles for all three inverter legs. However, when the phase current is not equal to zero, the nonlinear inverter voltage error may cause the output phase voltage to differ from zero [7]. This is illustrated in the first switching period in Fig. 3, where dotted line indicates ideal 50% duty cycle and the solid line represents the distorted real duty cycle, which is current direction dependent. To minimize the effect of the inverter voltage error, the commanded duty cycles in the zero-voltage injection PWM period may be set to 0% or 100% for all three inverter legs, as the second and third switching periods illustrated in Fig. 3.

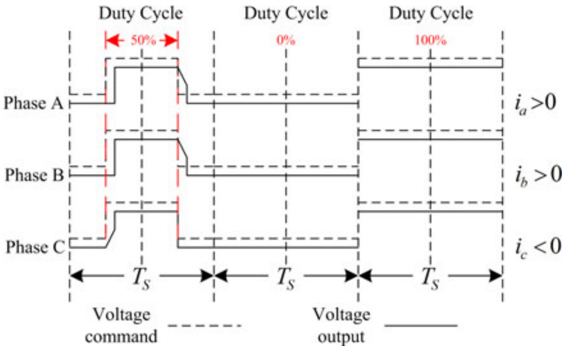

Fig. 3. Different duty-cycle strategies.

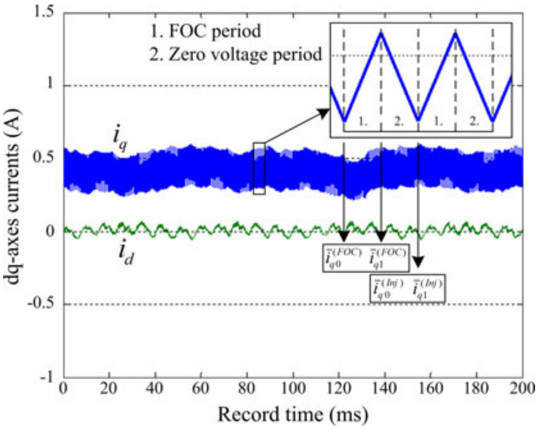

Fig. 4. Current variation with zero-voltage vector injection in steady state.

As shown in Fig. 2, in the FOC switching period and in the zero-voltage switching period, the corresponding voltage equations for the *q*-axis may be expressed as

$$v_q^{(\mathrm{FOC})} = Ri_{q0}^{(\mathrm{FOC})} + L_q \frac{d}{dt} i_q^{(\mathrm{FOC})} + \omega_r L_d i_{d0}^{(\mathrm{FOC})} + \omega_r \lambda_{\mathrm{mpm}} \tag{2}$$

$$0 = Ri_{q0}^{(\mathrm{Inj})} + L_q \frac{d}{dt} i_q^{(\mathrm{Inj})} + \omega_r L_d i_{d0}^{(\mathrm{Inj})} + \omega_r \lambda_{\mathrm{mpm}} \tag{3}$$

where di_q/dt term may be approximated by $(i_{q1} - i_{q0})/T_S$ and T_S is the switching period. When the machine operates at steady state, the *q*-axis current reference, which is determined by the speed loop PI, is constant. The current loop PI controller will only respond to the current measured at the beginning of the FOC switching period, which is $i_{q0}^{(\mathrm{FOC})}$. Therefore, the FOC switching period and the zero-voltage vector injection period may be regarded as one control period and it is therefore not needed to filter the current ripple caused by the zero-voltage vector injection for FOC. In steady state, current loop PI will ensure that the current sampled at the beginning of the control period ($i_{q0}^{(\mathrm{FOC})}$) will be the same, as the obtained experimental results shown in Fig. 4. This means the current variation caused

TABLE I
PARAMETERS OF SMPMSM

Parameters of SMPMSM			
Rated power [W]	470	Stator resistance [Ω]	2.35
Max. phase voltage [V]	380	*d*-axis inductance [mH]	10.0
Rated current [A]	2.9	*q*-axis inductance [mH]	13.4
Rated speed [r/min]	2850	PM flux linkage [Wb.turns]	0.13
Rated frequency [Hz]	95	Pole pairs	2

by the voltage generated in the FOC period will be opposite to the current variation in the next zero-voltage vector injection period, i.e., $\frac{d}{dt} i_q^{(\mathrm{FOC})} = -\frac{d}{dt} i_q^{(\mathrm{Inj})}$. Therefore, by adding (2) and (3), the term associated to the inductance will disappear. Considering a surface mounted PMSM (SMPMSM) with *d*-axis current controlled to be 0, (2) + (3) gives

$$v_q^{(\mathrm{FOC})} = v_q^* + \Delta v = R\left(i_{q0}^{(\mathrm{FOC})} + i_{q0}^{(\mathrm{Inj})}\right) + 2\omega_r \lambda_{\mathrm{mpm}} \qquad (4)$$

where v_q^* is the voltage command from FOC and Δv is the voltage error caused by the inverter.

To minimize the inverter voltage error effects, (4) may be applied for two different speeds (denoted with subscripts 1 and 2, respectively), as

$$v_{q1}^* + \Delta v = R\left(i_{q01}^{(\mathrm{FOC})} + i_{q01}^{(\mathrm{Inj})}\right) + 2\omega_{r1} \lambda_{\mathrm{mpm}} \qquad (5)$$

$$v_{q2}^* + \Delta v = R\left(i_{q02}^{(\mathrm{FOC})} + i_{q02}^{(\mathrm{Inj})}\right) + 2\omega_{r2} \lambda_{\mathrm{mpm}}. \qquad (6)$$

When the machine operates with a constant load or no load, the current on the *q*-axis may be regarded as constant for different speeds, i.e., $i_{q01}^{(\mathrm{FOC})} = i_{q02}^{(\mathrm{FOC})}$, $i_{q01}^{(\mathrm{Inj})} = i_{q02}^{(\mathrm{Inj})}$. Therefore, by subtracting (5) from (6), it yields

$$v_{q2}^* - v_{q1}^* = 2\left(\omega_{r2} - \omega_{r1}\right) \lambda_{\mathrm{mpm}}. \qquad (7)$$

Then, knowing the voltage command and speed, the PM flux linkage may be directly estimated. It does not involve the inductance and compensating the inverter voltage error is not necessary.

It should be noted that by injecting the zero-voltage vector, the position may be estimated directly from the measured current variation in that injection period. This sensorless scheme has been reported in details in [8], and the presented experimental results have shown a good accuracy of the estimated position. Therefore, the proposed new PM flux linkage estimation method based on the same zero-voltage vector injection principle in this paper is also suitable for sensorless operation.

IV. EXPERIMENTAL RESULTS

The proposed method discussed in Section III is tested on an experimental drive system. The experimental machine is an SMPMSM, the machine parameters are listed in Table I. A DSP-F28335 controller with an interface board, and a Danfoss FC302 series inverter are used for controlling the machine. A 2048 pulses incremental encoder is used for obtaining the real rotor position and speed.

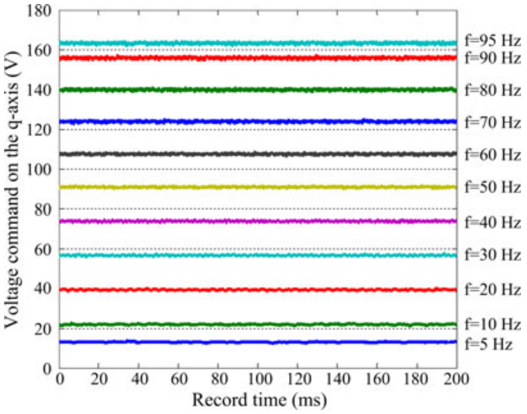

Fig. 5. Voltage commands at different speeds (sensored control).

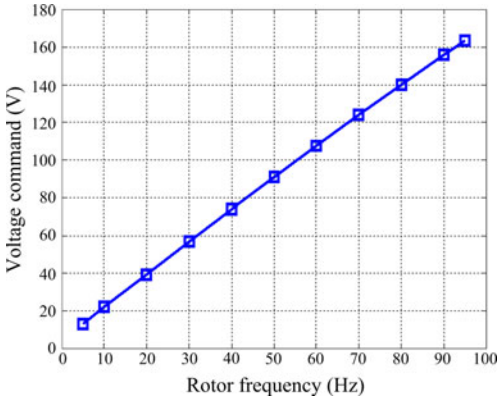

Fig. 6. Average value of the voltage command versus speed (sensored control).

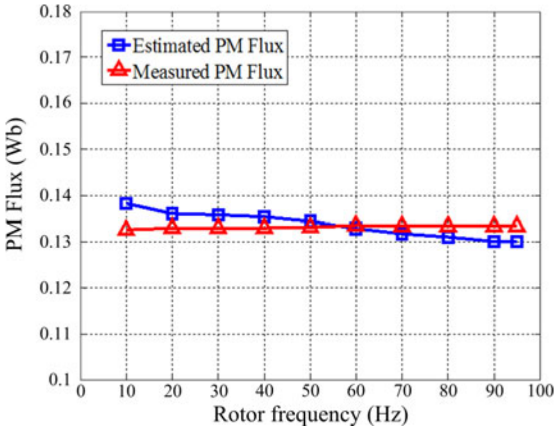

Fig. 7. Measured and estimated PM flux at different speeds (sensored).

A. Estimation in Sensored Control System

In this experiment, the rotor position and speed is obtained from the encoder. Fig. 5 shows the *q*-axis voltage commands recorded at different rotor electrical speeds. The voltage command is constant for a fixed speed, as shown in Fig. 5. The relationship between the average *q*-axis voltage command and the rotor speed in hertz is quite linear (with a constant slope) as shown in Fig. 6, which validates (7).

Fig. 7 shows the estimated PM flux linkage values by using (7). The measured PM flux linkage is from the open-circuit rotating test. It can be observed that the measured PM flux

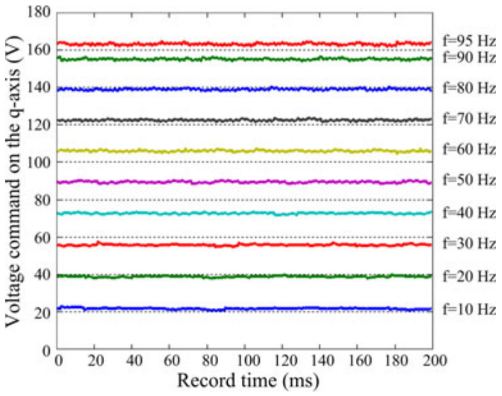

Fig. 8. Voltage commands at different speeds (sensorless control).

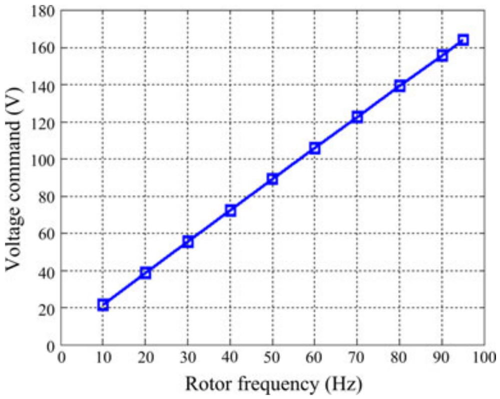

Fig. 9. Average value of the voltage command versus speed (sensorless control).

linkage is around 0.133 Wb. The online estimated PM flux linkage from (7) is between 0.138 Wb at 5 Hz and 0.130 Wb at 95 Hz. This corresponds to a small estimation error of −2.26–3.76%, with respect to the value measured from the open-circuit rotating test.

The slight decrease of the estimated PM flux linkage value when speed increases may be due to the increased q-axis current in order to overcome increased frictional torque at high speed. If this effect should be taken into account, then the resistance value should be known, and (7) will be modified to

$$v^*_{q2} - v^*_{q1} = R\left(\left(i^{(\mathrm{FOC})}_{q02} - i^{(\mathrm{FOC})}_{q01}\right) + \left(i^{(\mathrm{Inj})}_{q02} - i^{(\mathrm{Inj})}_{q01}\right)\right) + 2\left(\omega_{r2} - \omega_{r1}\right)\lambda_{\mathrm{mpm}}. \tag{8}$$

In this situation, the developed PM flux linkage estimation algorithm has the potential to be applied with different load profiles.

B. Estimation in Sensorless Control System

In this experiment, the rotor position and speed estimated from the zero-voltage vector injection method [8] are used as feedback signals for the FOC. The machine is, therefore, under sensorless control mode. Under this condition, the obtained q-axis voltage commands at different speeds are shown in Fig. 8. Comparing with Fig. 5, the voltage commands on the q-axis have more disturbances due to the noise in the estimated rotor speed.

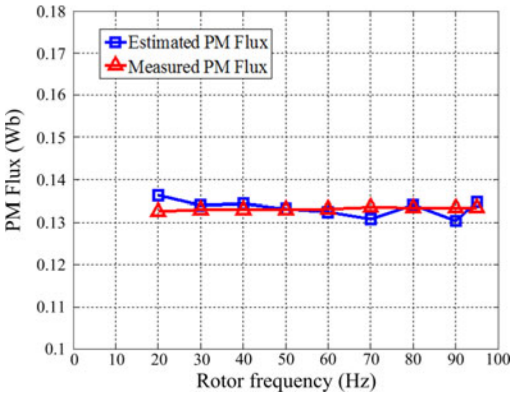

Fig. 10. Measured and estimated PM flux at different speeds (sensorless control).

Fig. 9 shows the average values of the q-axis voltage commands over 200 ms versus rotor speed. Fig. 10 shows the estimated PM flux linkage value by using (7). Compared to the PM flux linkage obtained from open-circuit test, the estimated ones exhibit an error between −2.26%–2.26% (the smallest value is 0.130 Wb, and the largest value is 0.136 Wb). The algorithm developed for PM flux linkage estimation can work well for sensorless operation of the drive system. This is an important feature since most of the drives are operated without an encoder.

V. CONCLUSION

This paper proposes a simple PM flux linkage estimation method based on zero-voltage vector injection. The new method is simple to implement. Only the voltage commands from FOC at different speeds are required for PM flux linkage estimation. The proposed method can be used for both sensorless and sensored drive system. The experimental results have shown an estimation error under 3.7% for different operation conditions.

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