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Online position error correction technique for sensorless control of multipole permanent magnet machines

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ABSTRACT

In order to improve the reliability of electric machine drive systems, the position encoder is often replaced with an estimator, such as the extended Kalman filter. However, estimation errors can still occur, especially in machines with high pole number, commonly used in renewable energy systems. The high number of pole pairs amplifies the effect of estimation errors, leading to a substantial divergence between actual and controlled currents, potentially causing harm to the machine through the excessive heat generation or demagnetization of permanent magnets. To address this issue, an error compensation method has been proposed and tested in a control scheme for a tidal stream system based on a multipole dual-star permanent magnet synchronous generator. The method estimates the position error by determining the q-axis permanent magnet flux and correcting it through a PI regulator. Simulation results demonstrate the effectiveness of the proposed method, even with a non-null initial rotor position.

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1. INTRODUCTION

The field oriented control (FOC) is commonly used to control AC machines due to its high performance. However, it relies on a position encoder to obtain the rotor position, which reduces its reliability, as the position encoder is a weakness in rotating machines based systems [1]–[3]. In this context, previous research has focused on sensor less control of AC machines by replacing the position encoder with an estimator [4]–[7]. However, only few explored the effect of the position error introduced by the estimation method [8]–[11]. Since the FOC is very sensitive to the rotor position, introducing an error in this parameter leads to incorrect control of machine currents, which can be harmful to the machine through excessive heat generation and/or permanent magnet (PM) demagnetization in PM machines [12]. This issue is, however only visible on machines with a high number of pole pairs, since the effect of the position error is amplified by the number of pole pairs of the machine [13], [14]. The details of the error position effect on a high pole number PM machines were previously discussed and published in our article [15].

A method for estimating the rotor position of PMSM using high-frequency signal injection was proposed in [16], but the impact of pole pair number and non-zero initial rotor position was not examined. An approach to estimate the initial rotor position was proposed in [17], but it is only effective when the machine is at rest. A modified MRAS speed observer with good speed estimation and negligible position error was developed in [18]. However, the impact of high pole number machines and non-zero initial rotor position on the control scheme and machine current was not studied. A method is proposed to correct position estimation error in a dual star PM synchronous generator (DSPMSG) by injecting current pulses in the two winding sets in order to detect any error in the position estimation [14]. However, it actually corrects errors in the machine parameters used in the model-based observer, and claims that the position error appears only because of parameter deviation, without considering the accuracy of the observer itself. The method proposed in [19] uses a low order harmonic suppression to detect and correct position estimation error. However, converter and machine faults also generate low order current harmonics, which may limit the effectiveness of the proposed correction method.

In this paper, a new method with a simple structure is proposed to compensate for the position error and ensure correct control of currents of a DSPMSG. The position error is estimated from the q-axis PM flux using a PI controller. The PM flux is oriented along the d-axis in the rotor reference frame, and since the reference frame used in the control scheme is shifted, a non-zero q-axis PM flux component appears. This component serves as input for a PI controller, which regulates it to zero. The output of the controller represents the position error, which is then added to the estimated position to obtain a more accurate value. The estimation of the PM flux is performed using the machine's equations in the d-q reference frame.

2. SYSTEM CONFIGURATION AND MODELLING

The proposed method is tested in a control scheme for DSPMSG controlled by two two-level three-phase converters, where outputs are connected in parallel to get a single DC bus, that feeds a standalone DC resistive load. Figure 1 shows a general scheme of the studied system. Figure 2 shows the coil configuration of a DSMSG, where the two stars of the stator are shifted by 30 electrical degrees, with isolated neutrals [20].

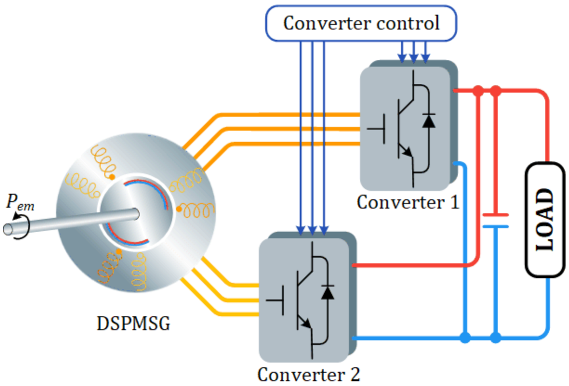


Figure 1. General scheme of the studied system

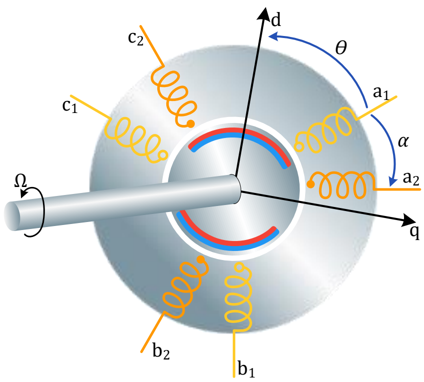


Figure 2. Dual star permanent magnet synchronous machine

The machine electrical behavior can be described by (1), where L_{abc} represents the inductance matrix of the machine given by (2). in this equation, L_{sl} is the leakage inductance, m the mutual inductance, L_{s2} is a harmonic coefficient generated by the rotor saliency, θ the rotor angle in respect to the magnetic axis of phase A1, θ_i, and θ_j are the displacement angles of phases i and j respectively [21]. It's clear that every term in the inductance matrix is dependent on the rotor position, which makes this model very heavy to simulate, and not appropriate to properly control the machine currents and speed [22]–[24].

$$v_{abc} = r\, i_{abc} + \frac{d}{dt}\left(L_{abc} i_{abc} + \varphi_{PM_{abc}}\right) \tag{1}$$

$$\begin{cases} L_{abc} = \begin{bmatrix} \begin{bmatrix} L_{a1} & M_{a1b1} & M_{a1c1} \\ M_{a1b1} & L_{b1} & M_{b1c1} \\ M_{a1c1} & M_{b1c1} & L_{c1} \end{bmatrix} & \begin{bmatrix} M_{a1a2} & M_{a1b2} & M_{a1c2} \\ M_{b1a2} & M_{b1b2} & M_{b1c2} \\ M_{c1a2} & M_{c1b2} & M_{c1c2} \end{bmatrix} \\ \begin{bmatrix} M_{a1a2} & M_{b1a2} & M_{c1a2} \\ M_{a1b2} & M_{b1b2} & M_{c1b2} \\ M_{a1c2} & M_{b1c2} & M_{c1c2} \end{bmatrix} & \begin{bmatrix} L_{a2} & M_{a2b2} & M_{a2c2} \\ M_{a2b2} & L_{b2} & M_{b2c2} \\ M_{a2c2} & M_{b2c2} & L_{c2} \end{bmatrix} \end{bmatrix} \\ L_i = L_{sl} + m + L_{s2}\cos\left(2(\theta + \theta_i)\right) \\ M_{ij} = m\cos\left(\theta_i - \theta_j\right) + L_{s2}\cos\left(2\theta + \theta_i + \theta_j\right) \end{cases} \tag{2}$$

In order to simplify the control algorithm, a simplified model, called extended d-q model, is often derived using the transformation matrix in (3), which results in the model given in (4) [25].

$$\begin{cases} T_p(\theta) = \frac{1}{\sqrt{2}}\begin{bmatrix} T(\theta) & T(\theta-\alpha) \\ T(\theta) & -T(\theta-\alpha) \end{bmatrix} \\ T(\theta) = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta-\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3}) \end{bmatrix} \end{cases} \tag{3}$$

$$\begin{cases} \frac{di_{nd}}{dt} = \frac{1}{L_{nd}}\left(v_{nd} - r_s i_{nd} + \omega_e L_{nq} i_{nq}\right) \\ \frac{di_{nq}}{dt} = \frac{1}{L_{nq}}\left(v_{nq} - r_s i_{nq} - \omega_e L_{nd} i_{nd} - \omega_e \sqrt{3}\Psi_{PM}\right) \\ \frac{di_{ad}}{dt} = \frac{1}{L_{ad}}\left(v_{ad} - r_s i_{ad} + \omega_e L_{aq} i_{aq}\right) \\ \frac{di_{aq}}{dt} = \frac{1}{L_{aq}}\left(v_{aq} - r_s i_{aq} - \omega_e L_{ad} i_{ad}\right) \end{cases} \tag{4}$$

ω_e is the electric frequency, and the terms L_x ($x = nd, nq, ad,$ or aq) are the cyclic inductances of the machine given in (5). Also, the mechanical behavior of the machine is described by (6). In this equation, J is the total inertia of the system, Ω the mechanical angular speed of the machine, T_m the mechanical torque applied on the machine shaft, and T_{em} the electromagnetic torque developed by the machine given in (7) [26]–[28].

$$\begin{cases} L_{ad} = L_{aq} = L_l \\ L_{nd} = L_{nq} = L_l + 3m \end{cases} \tag{5}$$

$$J\frac{d\Omega}{dt} = T_m - T_{em} - f\Omega \tag{6}$$

$$T_{em} = P\left(\varphi_{nd} i_{nq} - \varphi_{nq} i_{nd} + \varphi_{ad} i_{aq} - \varphi_{aq} i_{ad}\right) \tag{7}$$

3. PROPOSED CONTROL STRATEGY

The control strategy used in this work is the same as the one used un our previous work [15]. However, the proposed compensation technique is integrated in the control scheme as shown in Figure 3. First of all, lets explain the behavior of the control algorithm in the two situations, i.e., with and without position error. Applying the transformation (3) to the PM flux given by (8) (with Ψ_{pm} the amplitude of the PM flux) using the real rotor angle θ, results in (9).

As the d axis is oriented along the PM north pole, all the PM flux appears in this axis, and the flux in the q axis is null. But from the control point of view, the angle used to perform the coordinate transformation is $\hat{\theta}$ given by (10), so the PM flux in this case appears as in (11). It's clear that the q axis flux isn't null in this case, which can be resumed in Figure 4.

$$\varphi_{PM_{abc}} = \Psi_{pm}\begin{bmatrix} \cos(\theta) \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \\ \cos(\theta - \alpha) \\ \cos\left(\theta - \frac{2\pi}{3} - \alpha\right) \\ \cos\left(\theta + \frac{2\pi}{3} - \alpha\right) \end{bmatrix} \tag{8}$$

$$\varphi_{PM_{dq}} = \Psi_{pm}[\sqrt{3} \quad 0 \quad 0 \quad 0]^t \tag{9}$$

$$\hat{\theta} = \theta + \Delta\theta \tag{10}$$

$$\widehat{\varphi_{PM_{dq}}} = \sqrt{3}\Psi_{pm}[\cos\Delta\theta \quad -\sin\Delta\theta \quad 0 \quad 0]^t \tag{11}$$

The q-axis PM flux can be estimated using the machine's equations, and is given as (12).

$$\varphi_{PM_q} = \frac{1}{\omega_e}\left(-v_{nd} + ri_{nd} + L_{nd}\frac{di_{nd}}{dt}\right) - L_{nq}i_{nq} \tag{12}$$

If the position error $\Delta\theta$ is known and subtracted from the estimated angle $\hat{\theta}$, so the value of φ_{PM_q} should become null. As the error is not known, the value of φ_{PM_q} is used as input to a PI controller to estimate it, where $\Delta\theta$ is the output of the controller. Doing so, the error is continuously tuned until a null φ_{PM_q} is obtained. The estimated error is used to correct the angle used to perform the transformation as explained in Figure 4. A low pass filter is used to filter out undesirable high frequency oscillations and get a smooth estimation.

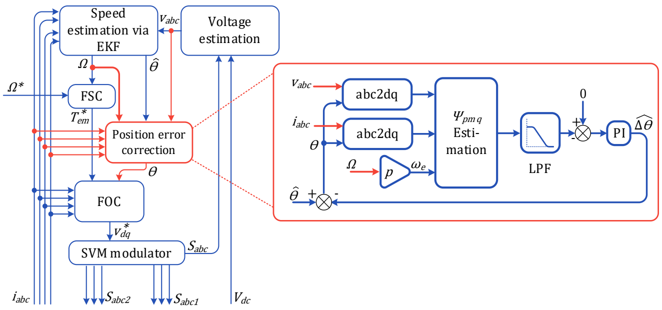


Figure 3. Proposed error compensation method

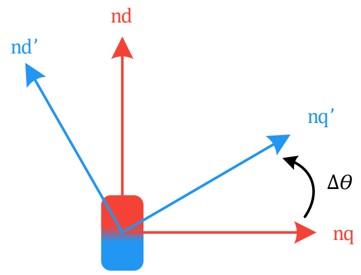


Figure 4. Configuration of the real dq frame and the one used in the control algorithm dq'

4. RESULTS AND DISCUSSION

The system was simulated in MATLAB/Simulink. A tidal stream system similar to the one used in [15] is used as prime mover for the machine. Initially, the simulation was run without any correction for position error. Next, the correction method was integrated, and new results were obtained. Finally, to evaluate the effectiveness of the proposed position error correction (PEC) technique in different conditions, the simulation was run again with a non-zero initial rotor position.

Figures 5(a) and 5(b) shows the actual and estimated speed of the machine with and without PEC. The results demonstrate a good tracking behavior and accurate speed estimation. No difference can be observed between the two figures; however, Figure 6 indicates that the PEC affects the accuracy of the EKF, leading to increased fluctuations in the speed estimation (maximum of 0.2% without correction and 0.5% with correction).

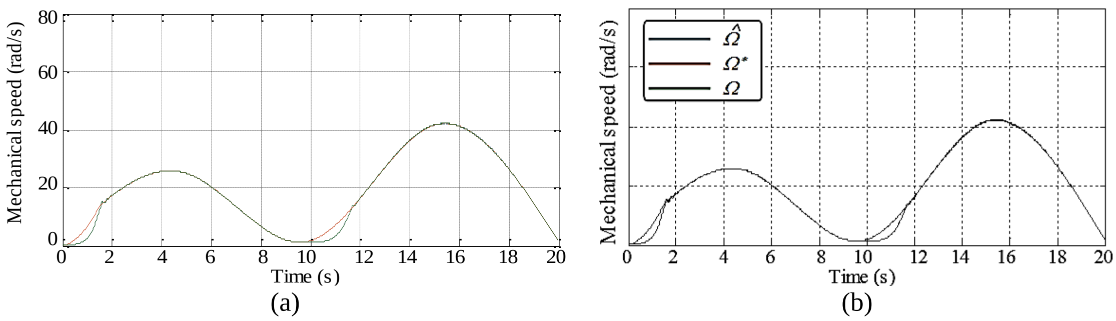


Figure 5. Actual and estimated speed of the machine: (a) without PEC and (b) with PEC

The fluctuations in speed estimation result in an error of 1.4 degrees in the estimated mechanical angle without PEC, as shown in Figure 7. This, in turn, leads to an electrical angle error that is eleven times higher, reaching 15.4 degrees. The figure also shows that the position error is higher when the correction is applied, but still correctly estimated with sufficiently high accuracy. The Figure 8 shows that due to this error, a high d-axis current is observed, as shown in Figure 8(a), despite the estimated current being kept at zero from the control point of view, as shown in Figure 8(b). Figure 8(a) also indicates that the correction is effective in eliminating the unwanted d-axis current, demonstrating the efficacy of the proposed compensation method. The actual q-axis current is presented in Figure 9. The Figure 9(a) shows that the actual q-axis current is 1.67 times higher than the estimated one when the proposed PEC is not applied. In cases of high position errors, the divergence becomes greater and more dangerous. The proposed PEC adjusts this current and ensures the system runs safely, as shown in Figure 9(b). Also, the second sub-machine's currents have not been affected by the correction as can be seen in Figure 10, which represents the currents with and without PEC.

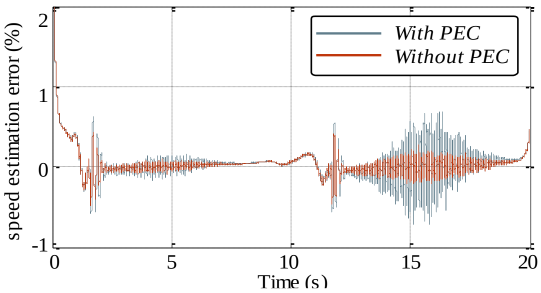


Figure 6. Speed estimation error evolution over time

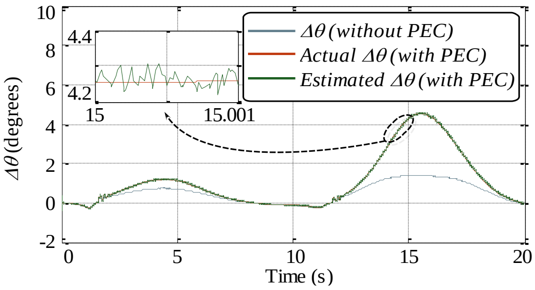
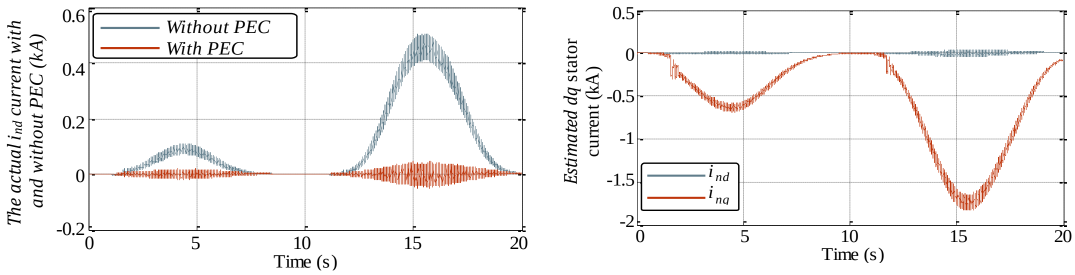


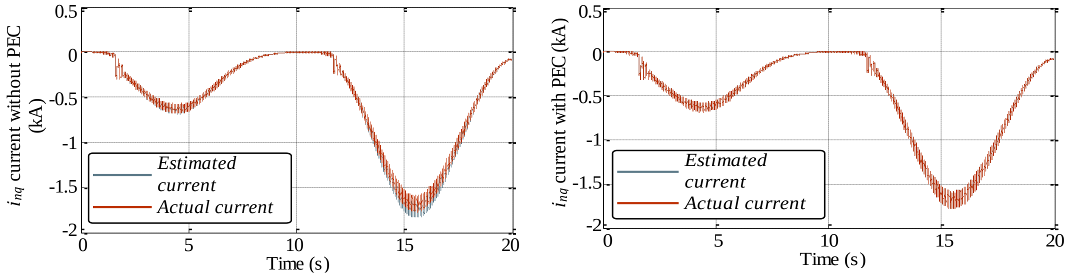
Figure 7. The actual and the estimated position error in mechanical degrees

After the initial results were presented, a non-zero initial rotor position of 7.27 degrees (80 electrical degrees) was applied in this test. As shown in Figure 11, the position correction PI controller quickly responds to the error and corrects it within 0.008 seconds. Figure 12 confirms that the currents are properly controlled and the d-axis current is maintained at zero.



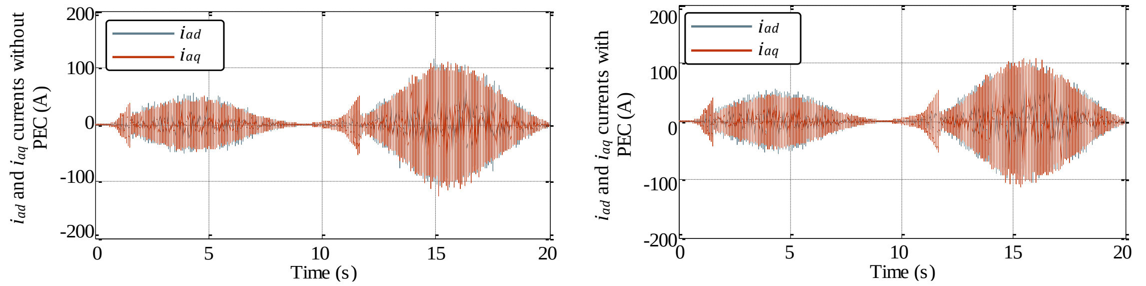
(a) (b)

Figure 8. Machine stator currents: (a) actual d-axis current and (b) estimated dq currents



(a) (b)

Figure 9. Actual and estimated q axis current: (a) without PEC and (b) with PEC



(a) (b)

Figure 10. The currents of the 2nd sub-machine, (a) without PEC and (b) with PEC

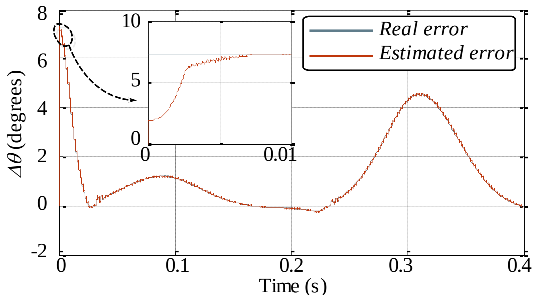


Figure 11. Actual and estimated electrical position error with a non-null initial position

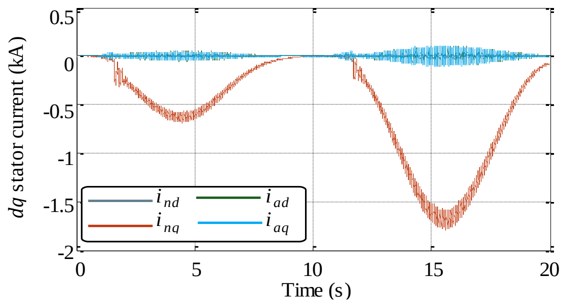


Figure 12. Actual currents when the PEC is applied with non-null initial rotor position

5. CONCLUSION

The field-oriented control is a widely used control strategy, but it requires the use of a position encoder for proper coordinate transformation. This makes it less reliable, particularly in applications requiring high reliability. The extended Kalman filter can help eliminate this drawback by estimating the machine's speed and position. However, no estimator can achieve 100% accuracy, therefore, small errors in position estimation can occur. This poses problems for multi-pole machines, as the mechanical angle error effect is amplified by the number of pole pairs, resulting in higher actual stator currents than those seen by the control system. This can cause various types of damage to the machine, including overheating, and saturation.

A technique is proposed in this paper, which is capable of estimating the position error and compensate it in order to get a more accurate and reliable control algorithm for a dual star PMSM. Firstly, the q-axis PM flux is estimated basing on the machine's electrical equations, and then a PI regulator is used to estimate the position error using the q-axis PM flux component. The real d-q reference frame is oriented along the PM poles, but because of the position error, the reference frame used in the control algorithm is shifted in respect to the PM poles, therefore, the q-axis PM component is no longer null. Simulation results show a good accuracy in estimating the position error, which confirms the effectiveness of the proposed technique. The technique is also tested in case of non-null initial rotor position, and it showed up good behavior, and is capable of estimating and correcting the error very quickly.

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