Pulsating Signal Injection-Based Axis Switching Sensorless Control of Surface-Mounted Permanent-Magnet Motors for Minimal Zero-Current Clamping Effects

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Abstract—In this paper, we propose an injection-based axis switching (IAS) sensorless control scheme using a pulsating high-frequency (HF) signal to minimize position detection error and velocity estimation ripple resulting from the zero-current-clamping (ZCC) effect for surface-mounted permanent-magnet motors. When a pulsating carrier-signal voltage is injected in an estimated synchronous frame, the envelope of the resulting HF current measured in the stationary reference frame follows an amplitude-modulated pattern. Using this information, the IAS technique allows one to avoid multiple zero crossings of HF currents by adjusting the current phase angle according to the load condition. At no-load condition, the pulsating voltage is injected only on the $d$-axis, while the $d$-axis current is controlled to a certain nonzero value. Under a load condition, the injection voltage is switched to the $q$-axis, while the $d$-axis current drops back to zero. Thus, the proposed sensorless control enforces a much better estimation performance in a region of ZCC without a predefined offline commissioning test than the standard pulsating injection scheme. Experiments illustrate the effectiveness of the proposed method in suppressing the estimation error caused by the ZCC disturbance and in extending the system bandwidth.

Index Terms—Estimated position error and velocity ripple, injection-based axis switching (IAS) sensorless control, pulsating high-frequency (HF) signal injection, zero-current-clamping (ZCC) effect.

I. INTRODUCTION

A

NUMBER of carrier-signal injection techniques have been proposed for the sensorless zero-low-frequency control of ac motors [1]. With advances in motor design oriented to high-frequency (HF) sensorless control and signal injection technologies and with the evolution of the angle tracking technique, opportunities are increasing for applications of high-performance ac motor drives [2], [3].

Normally, these sensorless schemes allow a parameter-independent rotor position estimation even in a zero-low-frequency operation. However, the HF signal forces the phase current to have multiple zero-crossings when the fundamental phase current is close to zero. The zero-current-clamping (ZCC) effect that is relevant to multiple zero-crossings causes disturbances that significantly affect the quality of the position estimate [4]–[6]. With the presence of the ZCC effect, the HF signal injection-based sensorless controllers are prone to position error ripples. This side effect significantly limits the current/velocity control bandwidth and the dynamic response of the motor torque that can be achieved and eventually results in a loss of field orientation.

One solution to this problem has involved a complicated lookup table based on experimental data of the phase current and the actual rotor position [4]. An interesting correction method based on ZCC modeling for a periodic HF signal in a stationary reference frame has recently been proposed in [6] where the compensation result leads to an accurate position estimate without lookup tables. For a pulsating HF signal injection, the modeling of the voltage distortion is also developed, and its effect is examined on the phase current with the HF signal for the purpose of cancellation of the ZCC effect [7]. Within this framework, a distortion factor is introduced to represent the associated ZCC distortion around the zero-crossing of the fundamental current. Then, an offline commissioning technique has proven to be effectively capable of obtaining the stator inductances of the motor in addition to estimating the corresponding distortion factor.

These previous remedies for solving ZCC problems have involved some offline commissioning tests that have been required to obtain a record of the disturbance signatures. These remedies have resulted in an immense engineering effort because they have required a number of load tests and multiple data gathering processes. The commissioning test must be done for every single motor and injection condition. This means that numerous iterative checks are needed to ensure that the sensorless controller operates within the performance specified by the manufacturer. Thus, this may be undesirable in an industrial sense [8].

This paper proposes a specific pulsating HF sensorless control architecture suitable for practical implementation. For this purpose, we utilize an injection-based axis switching (IAS)
sensorless scheme using a pulsating HF signal to minimize the ZCC effect for surface-mounted permanent-magnet (SMPM) motors. When a pulsating carrier-signal voltage is injected in a synchronous frame, the envelope of the resulting HF current measured in the stationary reference frame follows an amplitude-modulated pattern with a maximum to zero magnitude. Taking this effect into account, multiple zero-crossings of HF currents around the zero-crossing region can be avoided by adjusting the current phase angle according to the load condition. At no-load condition, the pulsating voltage is injected only on the d-axis, while the d-axis current is controlled to a certain nonzero value. Under a load condition, the injection voltage is switched to the q-axis, and the d-axis current drops back to zero. Thus, the proposed injection scheme permits the HF current magnitude to be zero at every zero-crossing point. The minimization result leads to an accurate position estimate when in a ZCC region, and the proposed scheme does not require any additional efforts supported by sophisticated offline tests. The proposed method does not depend on the motor saturation characteristic, the injected voltage/frequency condition, and the digital implementation.

### II. Analysis of the ZCC Effect Under A Pulsating HF Signal Injection

If an HF voltage with a carrier frequency \( \omega_c \) is added to the \( d \)-axis control output in the estimated \( dq \) synchronous reference frame, the injection voltage vector can be given by

\[
\begin{bmatrix}
\hat{v}_{dh}^e \\
\hat{v}_{qh}^e
\end{bmatrix} = \begin{bmatrix} V_h \cos \omega_c t \\ 0 \end{bmatrix}.
\]  

(1)

In general, the resulting HF current in the \( \alpha \beta \) stationary frame can be described as

\[
\begin{bmatrix}
i_{\alpha h} \\
i_{\beta h}
\end{bmatrix} = T^{-1}(\hat{\theta}_r) \begin{bmatrix}
\hat{v}_{dh}^e \\
\hat{v}_{qh}^e
\end{bmatrix} = \begin{bmatrix}
i_{\alpha h}^e \\
i_{\beta h}^e
\end{bmatrix} \sin \hat{\theta}_r
\]  

(2)

where \( \hat{\theta}_r \) represents the estimated electrical rotor angle and \( \hat{v}_{dh}^e (= I_h \sin \omega_c t) \) indicates the resulting \( d \)-axis HF current in the estimated rotor reference frame. Under the balanced three-phase conditions, the instantaneous fundamental currents are

\[
i_{\alpha f} = I \cos (\hat{\theta}_r + \phi) \\
i_{\beta f} = I \cos \left( \hat{\theta}_r - \frac{2\pi}{3} + \phi \right) \\
i_{\gamma f} = I \cos \left( \hat{\theta}_r + \frac{2\pi}{3} + \phi \right)
\]  

(3)

where \( I \) represents an instantaneous fundamental current amplitude and \( \phi (= \tan^{-1}(\hat{v}_{dh}^e / \hat{v}_{dh}^q)) \) is an arbitrary \( dq \) fundamental current phase angle.

Then, the motor phase current can be expressed as

\[
i_{\alpha s} = \begin{bmatrix} i_{\alpha f} + i_{\alpha h} \\
i_{\beta f} + i_{\beta h}
\end{bmatrix} = \begin{bmatrix} I \cos(\hat{\theta}_r + \phi) + \hat{v}_{dh}^e \cos \hat{\theta}_r \\
I \sin(\hat{\theta}_r + \phi) + \hat{v}_{dh}^e \sin \hat{\theta}_r
\end{bmatrix}.
\]  

(4)

It can be noticed from (4) that the phase current can be resolved into two components and that the envelope of the resulting HF current varies sinusoidally in \( \hat{\theta}_r \). The position of the maximum or zero magnitude of the HF component is determined by the phase angle \( \phi \). When the fundamental phase current crosses the zero-crossing region, the HF current results in a voltage error due to the ZCC effect. The disturbance voltage error around the zero-crossing region is of the same carrier frequency and in phase with the HF current [6]. This distortion ripple in the estimated position signal has a direct impact on the quality of the sensorless control performance. The fact that the envelope of the HF current can be changed by the phase angle is an important conceptual step in understanding ZCC compensation in the pulsating signal injection-based sensorless controls. Table I shows the relationship of the phase angle versus the HF current distribution in accordance with the injection axis. In the \( d \)-axis injection as in (1), HF current envelopes can be classified into three categories in accordance with the phase angle or the load condition.

<table>
<thead>
<tr>
<th>Phase Angle</th>
<th>D-axis injection</th>
<th>Q-axis injection</th>
<th>Motor Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>( i_{qf} = 0 )</td>
</tr>
<tr>
<td>( \pi/2 )</td>
<td></td>
<td></td>
<td>( i_{qf} \neq 0 ) and ( i_{df} = 0 )</td>
</tr>
<tr>
<td>( 0 &lt; \phi &lt; \pi/2 )</td>
<td></td>
<td></td>
<td>( i_{qf} \neq 0 ) and ( i_{df} \neq 0 )</td>
</tr>
</tbody>
</table>

A. \( \phi = 0 \)

The phase angle becomes zero at no-load condition. The motor currents are

\[
i_{\alpha s} = \begin{bmatrix} i_{\alpha f} + i_{\alpha h} \\
i_{\beta f} + i_{\beta h}
\end{bmatrix} = \begin{bmatrix} I \cos \hat{\theta}_r + \hat{v}_{dh}^e \cos \hat{\theta}_r \\
I \sin \hat{\theta}_r + \hat{v}_{dh}^e \sin \hat{\theta}_r
\end{bmatrix}.
\]  

(5)
The current waveform is shown graphically in Table I. The aforementioned modulation of the HF current will not produce distortion due to the ZCC effect at every zero-crossing point where the HF current amplitude naturally becomes zero. This means that the position estimate error due to the ZCC effect will be minimized in this mode without any sophisticated compensation scheme or additional offline test.

B. \( \varphi = \pi/2 \)

In this case, the \( q \)-axis current has a nonzero value for motor torque generation, while the \( d \)-axis current remains zero. This situation corresponds to the normal operation of an SMPM motor under a load condition. The motor currents are

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = \begin{bmatrix}
i_{d} + i_{a_h} \\
i_{q} + i_{b_h}
\end{bmatrix} = \begin{bmatrix}
-I \sin \hat{\theta}_r + \frac{\hat{\theta}_r}{r} \\
-I \cos \hat{\theta}_r + \frac{\hat{\theta}_r}{r}
\end{bmatrix}.
\]  
(6)

The maximum value of the HF current is located at a zero-crossing, as shown in Table I. This type of HF current distribution will cause the worst position estimate error due to the ZCC effect. This implies that larger distortions are observed for the case of a higher voltage injection which is usually favored for a better signal-to-noise ratio. Unless properly decoupled, it can result in a noticeable estimated position error or even stability problems.

C. \( 0 < \varphi < \pi/2 \)

In this mode, both currents have a nonzero value for the motor torque and the stator flux generation. This situation usually appears in the normal operation of an induction machine. The motor currents are

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = \begin{bmatrix}
i_{d} + i_{a_h} \\
i_{q} + i_{b_h}
\end{bmatrix} = \begin{bmatrix}
I \cos (\hat{\theta}_r + \varphi) + \frac{\hat{\theta}_r}{r} \\
I \sin (\hat{\theta}_r + \varphi) + \frac{\hat{\theta}_r}{r}
\end{bmatrix}.
\]  
(7)

The superimposed HF current of Table I can also cause a significant position estimate error around the zero-crossing region.

This analysis interprets the choice of the zero phase angle (\( \varphi = 0 \)) in the \( d \)-axis injection and the phase angle of \( \pi/2 \) in the \( q \)-axis injection as an indicator of the minimum ZCC effect.

III. IAS SENSORLESS CONTROL

According to the analysis presented in Section II, we find that the phase angle is closely linked to the distribution of the HF current in the pulsating signal injection-based sensorless control. This relationship implies that the adjustment of the injection axis and the phase angle is needed in such a way that the zero magnitude of the HF current is always achieved at every zero-crossing point of the phase current. The simplest way to adjust the phase angle is to change the \( d \)-axis current in the SMPM motor which is conventionally controlled to zero for efficiency purposes.

In order to achieve this goal, the pulsating voltage is injected only on the \( d \)-axis at no-load condition, while the \( d \)-axis current is controlled to a certain nonzero value. This action drives the phase angle to be zero (\( \varphi = 0 \)). In contrast, under a load condition, the injection axis is switched to the \( q \)-axis as in (8), and the \( d \)-axis current drops back to zero

\[
\begin{bmatrix}
\hat{v}_{dh} \\
\hat{v}_{qh}
\end{bmatrix} = \begin{bmatrix}
0 \\
v_h \cos \omega c t
\end{bmatrix}.
\]  
(8)

In this case, the \( d \)-axis HF current in the estimated rotor reference frame is used for the extraction of the rotor position and velocity information. This action results in a phase angle of \( (\pi/2) (\varphi = \pi/2) \). Then, the zero magnitude of the HF current is always achieved at every zero-crossing point. This means that the ZCC effect can be inherently minimized under all operating conditions.

Fig. 1(a) shows an overall block diagram of the proposed IAS sensorless strategy. This structure leads to a simple design which avoids the complexity of having an additional compensator to ensure accurate position estimates. The IAS is performed using a block called the “injection axis selector,” as shown in Fig. 1(b). In the \( d \)-axis injection phase, the \( q \)-axis injection is off, and the \( d \)-axis current command is maintained as a prescribed value \( i^*_e d \). When the \( q \)-axis current reaches the transition value \( i^e _{q, th} \), the \( q \)-axis injection can be turned on, and the \( d \)-axis current drops back to zero. In this paper, we advocate a hard-axis switching from the \( d \)- to the \( q \)-axis because a gradual conversion requires a more complex signal processing or angle estimation scheme during the overlap interval.

A simple strategy for the \( d \)-axis current command is proposed to minimize multiple zero-crossings of HF currents in the ZCC region

\[
i^*_e d > I_{ZCC} + I_h
\]  
(9)

where \( I_{ZCC} \) is the fundamental current amplitude when the equivalent trailing time reaches zero [6]. Notice that if \( i^* _{e q, th} \) is chosen to be less than \( I_{ZCC} \), the motor phase current can be trapped within the ZCC boundary. This situation can easily occur in a light-load condition and gives a negative impact on the quality of the sensorless control performance. This means that a threshold of \( i^* _{e q, th} \) should be larger than a value of \( I_{ZCC} \) to avoid estimated angle distortions

\[
i^* _{e q, th} > I_{ZCC}.
\]  
(10)

In the \( d \)-axis injection for \( 0 \leq i^* _{e q, th} \leq I_{ZCC} \), the HF current will not produce any noticeable distortion owing to \( i^*_e d \) that is larger than \( I_{ZCC} \).

This guideline does not require any additional effort to seek \( I_{ZCC} \) since ZCC decoupling of the fundamental current requires a predetermination of the equivalent-trailing-time trajectory with respect to the current amplitude [9].

IV. EXPERIMENTAL RESULTS

The proposed algorithm is implemented on a 600-W SMPM motor described in Table II. The PWM inverter consists of 10-kHz switching insulated-gate bipolar transistor modules, and the dead time is 3.5 \( \mu \)s. Two-phase currents are sampled with a rate of 50 \( \mu \)s, and the fundamental current regulator is
tuned for a 3000-rad/s bandwidth. An encoder of 2500 pulses per revolution is mounted to one end of the SMPM motor shaft to monitor the actual rotor position and velocity. The other end of the shaft is coupled with a 750-W dc motor in order to apply the load torque. The injection condition has been set to 10 V–850 Hz, and the rotor position estimation is obtained through a signal processing method using second-order discrete-time Butterworth band-pass filters and band-stop filters. A simple tracking observer is used to estimate the rotor position, as shown in Fig. 1(c) [2]. The closed-loop eigenvalues denoted by $L_1$, $L_2$, and $L_3$ are set at 100 Hz. With lower bandwidth, undesirable ripples due to secondary saliencies can be filtered out, but such a filtering might induce a lag in the estimated signal.

From the experimental work carried out during this research, it was found that the value of $I_{ZCC}$ is in the range of 20% of rated current. The $d$-axis current command is obtained using (9), which is about 2 A. One potential impact of the proposed scheme includes increased losses caused by $i_{do}^e$. This is a strong function of the stator resistance and the magnitude of $i_{do}^e$.

Fig. 1. Proposed IAS sensorless scheme. (a) Overall control structure. (b) Block diagram of the injection axis selector. (c) Block diagram of the signal processing and angle controller.
TABLE II
RATINGS AND KNOWN PARAMETERS OF THE SMPM MOTOR UNDER TEST

<table>
<thead>
<tr>
<th>Ratings and Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power output</td>
<td>600</td>
<td>W</td>
</tr>
<tr>
<td>Rated current / speed</td>
<td>5.1/3000</td>
<td>Apeak / r/min</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>4</td>
<td>poles</td>
</tr>
<tr>
<td>Stator resistance / inductance</td>
<td>0.714/4.59</td>
<td>Ω / mH</td>
</tr>
<tr>
<td>$i_{q,th}$ and $i_{ds}$</td>
<td>1.27/2</td>
<td>Apeak</td>
</tr>
<tr>
<td>$I_{ZCC}$</td>
<td>1</td>
<td>Apeak</td>
</tr>
</tbody>
</table>

![Figure 2](image1.png)

Fig. 2. Measured rotor position estimation error due to cross saturation for various $d$- and $q$-axis currents.

![Figure 3](image2.png)

Fig. 3. Resulting 2-D trajectory used in the controller.

test motor, we observe that the additional loss amounts to 0.47% rated power. In the testing system, the transition value $i_{q,th}$ is set to 25% rated current considering the value of $I_{ZCC}$. Here, the drive is operated under sensorless control.

Fig. 2 shows the measured 3-D full data of the estimated rotor position error due to the cross-saturation effect [10], [11]. Here, two 2-D trajectories of Fig. 3 were used in the controller because the test was done at $i_{ds} = 0$ and 2. The cross-saturation effect is compensated by employing the approximated polynomial from the nonlinear trajectory.

Fig. 4 shows time-domain responses of the standard pulsating signal injection sensorless control [2], [3] without the injection axis switching at 30 r/min. In this test, the $d$-axis fundamental current of 2 A is intentionally added to compare to the proposed scheme. Initially, the HF voltage is injected on the $d$-axis, while the $d$-axis current is controlled to be 2 A. The phase angle is near zero. The $q$-axis current jumps to the rated current gradually when a load is applied up to 100%. After the loaded operation, it can be seen that a significant distortion with six times the fundamental frequency is evident in the enlarged estimated position signal and the phase current [Fig. 4(a)] because the phase angle is somewhere between 0 and $\pi/2$. When a higher load is applied, a larger distortion is expected. These spike ripples significantly limit the current control bandwidth and the dynamic response of the motor torque that could be achieved and may eventually result in a loss of field orientation.

The bandpass-filtered HF current envelope and the synchronous $d-q$ axis current are shown in Fig. 5 for the same working condition as that in Fig. 4. A close inspection of the HF current envelopes shows visible perturbations in every zero-crossing point of the phase current. The perturbation gives a direct impact on the quality of the sensorless control performance. The result shows a good agreement with the analysis of the ZCC effect based on the relationship between the phase angle and the HF current distribution.

Another interesting experimental results based on the standard approach with the zero $d$-axis fundamental current are described in Fig. 6. In this test, the phase angle reaches $\pi/2$ under the load condition. From Fig. 6, it can be observed that disturbances in all measured waveforms stay at a larger level than those of Fig. 4. This result provides a key measure for the worst case behavior on ZCC distortions in the test system.

Fig. 7 shows the performance of the proposed IAS scheme. The other conditions are the same as those of Fig. 5.
Fig. 5. Standard pulsating signal injection under a rated load. (a) Enlarged responses of the shaded part in (b) and (c). (b) Bandpass-filtered HF current envelope in the stationary reference frame. (c) Motor phase current. (d) $d$-axis current in the estimated rotor reference frame. (e) $q$-axis current in the estimated rotor reference frame.

Fig. 6. Standard pulsating signal injection with the zero fundamental $d$-axis current (full load). (a) Enlarged responses of the shaded part in (b), (c), and (d). (b) Motor phase current. (c) Bandpass-filtered HF current envelope in the stationary reference frame. (d) Estimated rotor angle. (e) Position error.

\[
\hat{e}_q = e_q - \hat{\delta}_q, \quad \text{the HF voltage injection axis is switched to the}\ q\text{-axis. In the enlarged estimated position signal and the phase current [Fig. 7(a)], the improvement is clearly visible. The residual distortion in the position error is mainly the result of the cogging effect of the motor. Compared to the case with the standard pulsating signal injection-based sensorless control, the position error plot shows that the maximum amplitude is greatly reduced to less than $\pm 5$ electrical degrees under a full-load condition. It is concluded that the proposed algorithm could provide reliable position estimation performance in a real situation without any additional compensation schemes and commissioning procedures.}

The same experiment, under the proposed IAS scheme, is repeated, as shown in Fig. 8. Note that the $d$-axis current in
Fig. 8(d) drops back to zero immediately when the IAS occurs. This means that the phase angle remains $\pi/2$ in the IAS scheme under the load condition. The axis switching performance of the proposed algorithm is directly affected by the accuracy and the resolution of acquisition data for the compensation of the cross-saturation effect. Hence, it is necessary to experimentally acquire an accurate map for the cross saturation or decouple its effect online. All of the zero-magnitude points of the HF current in Fig. 8(a) are exactly synchronized with the phase current zero-crossings irrespective of the load condition.

Particular attention should be paid to the estimated velocity which is the derivative of the estimated position. This feature makes the estimated velocity much more vulnerable to noise resulting from secondary saliencies. The velocity control performance not only depends on the bandwidth of the angle estimator and the velocity controller but also on the magnitude of noise harmonics. The noise can be filtered with added lag to the position/velocity estimate, but the system then becomes sluggish.

To demonstrate the differences in the perspective of the velocity estimation, a comparative test is performed, as shown in Fig. 9. From the top to the bottom, the $q$-axis phase current in the estimated rotor reference frame, the real velocity from the encoder, the estimated velocity, and the velocity error are depicted. With the standard sensorless control [Fig. 9(a)], the steady-state velocity estimation error and ripples increase during the loaded operation. These may cause a system instability problem, depending on the mechanical system condition and the control bandwidth. When IAS sensorless control is applied [Fig. 9(b)], the velocity ripples are kept to a minimum irrespective of the load condition.

The performance of the proposed method is investigated through experiments at the half-load condition. Since we are primarily interested in the IAS response in this test, the load is changed much faster than that of Figs. 7 and 8. The corresponding experimental results are plotted, as shown in Figs. 10 and 11. The zoomed plots in Figs. 10(a) and 11(a) show the instant when the injection axis is switched to the $q$-axis. The test result indicates that the stable operation is sustained in the rapid-load-change condition. Using the IAS scheme, a considerable improvement for steady-state performance can be achieved without using an additional commissioning effort.

This kind of algorithm is particularly helpful when working with inexperienced users or a new employee.

From the experimental results, it can be concluded that the stability and the dynamics of the closed-loop system combining the controller and the angle observer are much improved by the proposed scheme.

V. CONCLUSION

This paper has proposed a specific pulsating HF sensorless control architecture with the IAS for SMPM motor drives. Specifically, an analysis was presented which accurately describes the ZCC effect from the perspective of a pulsating HF signal injection. Based on the analysis, at light-load condition, the pulsating voltage is injected only on the $d$-axis, while the $d$-axis current is controlled to a certain nonzero value. Under a heavy-load condition, the injection axis is switched...
to the $q$-axis, while the $d$-axis current drops back to zero. The proposed method does not depend on the motor saturation characteristic, the injection voltage/frequency condition, and the digital implementation. The IAS sensorless controller greatly reduces the additional offline commissioning effort while achieving a comparable performance as a fully calibrated conventional compensator. Intensive test results demonstrate that the proposed compensation scheme could provide a considerable improvement in the estimated performance and the control bandwidth. Although the proposed method is promising, more research is required for application to other ac motors such as induction motors and synchronous reluctance motors.

**References**


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