Frame Alignment Stability Issues in Natural Field Orientation

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Abstract—Natural field orientation (NFO) is a technique for generating a rotating reference frame position for an induction machine aligned with the stator flux. The term “natural” is applied because there is an implicit tendency for the rotating frame to realign with the correct stator flux frame position if there is a perturbation away from this position. However, under regeneration conditions this realignment property does not occur, and the frame position, if perturbed, will move the control reference frame away from stator flux alignment. This paper examines this frame alignment stability problem and proposes a solution that retains the features and simplicity of the NFO concept.

Index Terms—Natural field orientation (NFO), reference frame stability, vector control.

I. INTRODUCTION

FIELD-ORIENTED control (FOC) of induction machines is now a very mature area with many commercial applications. Since its initial introduction by Blaschke [1], considerable research has taken place to refine the basic idea and to overcome problems and issues related to practical implementation.

Much of the research in FOC techniques has concentrated on two main areas.

1) Techniques for accurately locating the field position in induction machines. This is problematic as the required field positions cannot be directly measured from stator terminal measurements, and some estimation is required.

2) Methods of implementing sensorless control of the machine. The terms “sensorless” in this context means that there is no shaft position sensor or speed transducer. Therefore, field location information, as well as the shaft speed, have to be determined without the use of this sensor.

Natural field orientation (NFO) is a patented concept that was first developed in the 1980s [2], [3]. It is an alternative to FOC for field location in an induction machine. Because it functions without requiring a speed or shaft position sensor, it is particularly amenable to sensorless control.

Fig. 1 shows the basic idea of NFO as first presented in the initial patents. One can see that the algorithm essentially transforms the induction machine into a voltage-fed dc machine, where the equations for the transformed $x$ and $y$ axes can be shown to be [4]

$$u_x = R_s i_x + L_m \frac{d|i_m|}{dt}$$

(1)

$$u_y = R_s i_y + \omega_m L_m |i_m|$$

(2)

where $|i_m|$ is the stator magnetizing current (which is coincident with the stator flux vector), $\omega_m$ is the angular velocity of the stator flux vector, and $L_m$ is the magnetizing inductance. These equations are identical to the field and armature equations, respectively, for a separately excited dc machine.

NFO is closely related to stator flux orientation (SFO). The essential idea behind NFO is that if one can sense the stator flux voltage, then assuming that the flux is at a constant value, the stator flux vector will be 90° spatially lagging this voltage. One does not estimate the stator flux magnitude; as the strategy assumes that the flux is at the reference value. This is a crucial difference between NFO and SFO, and leads to the main advantages it has over traditional SFO.

Remark 1: The last sentence of the previous paragraph is very important with respect to the NFO technique. If one assumes that the stator flux is at the reference level, using the magnitude of the stator flux voltage will allow estimation of the angular velocity of the stator flux vector. This angular velocity can then be integrated to give a less noisy estimate of the stator flux position in the machine compared to using the instantaneous value obtained from the stator flux voltage.

Remark 2: NFO falls into the voltage model classification of flux estimators [5]. The stator flux voltage can be estimated with the following expression:

$$e_m = u_s - R_s i_s$$

(3)

where $e_m$ is the stator flux voltage space vector, $u_s$ is the input terminal voltage space vector, and $i_s$ is the stator current space vector. Note that the estimation of $e_m$ only requires knowledge of the $R_s$ parameter.

A well-known alternative algorithm to estimate flux is based on the current model of the rotor [1], [5], [6]. However, this approach requires knowledge of the rotor resistance and the rotor speed (or an estimate of it). The main advantage of the current model flux estimation approach is that it works at very low speeds because it does not use voltage integration to find the flux (as the voltage model-based SFO does). Its
Fig. 1. Induction machine converted to a dc machine using NFO.

Fig. 2. Block diagram of an NFO control system.

main disadvantage is that it is reliant on knowledge of the rotor resistance and requires a measurement or estimate of the rotor speed. The strategy in the past has been to combine the voltage and current model flux estimators, with the current model being used at low speed, and a transition to the voltage model occurring at higher speeds.

Fig. 2 shows the block diagram of basic NFO orientated to the stator flux vector. Fig. 3 shows the block diagram of a voltage model-based SFO scheme where the flux estimation is also executed in the estimated field frame. It is well-known that SFO suffers from voltage integration problems when estimating the flux, particularly at low speeds. Much of the research into SFO has been focused on solving this problem [7], [8]. A unique feature of NFO is that it does not use integration to derive/generate the machine flux. This means that the algorithm will not be as sensitive to stator resistance errors compared to the voltage model-based SFO, and there are no low speed voltage integration issues. Furthermore, the problem of initializing the voltage integrator, present with SFO, does not occur in NFO.

Remark 3: One other key difference in the NFO algorithm compared to the traditional form of flux estimator for vector control is that the flux is calculated relative to the estimated reference frame. Fig. 4 shows the arrangement for most flux estimation algorithms with respect to the reference frame conversion process—the flux estimator (either a voltage or current model-based one) is operating in the stationary frame. From Fig. 2 one can see that NFO flux estimation is based on using variables that have been converted to the flux reference frame.

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*One can also develop NFO in the rotor flux frame.*
Therefore, there is a circular dependence in NFO that is not present in Fig. 4. It is the stability of this dependence, under regeneration conditions, that is the main focus of this paper.

There have been a number of successful implementations of NFO control reported in the literature [9]–[11]. However, as shall be demonstrated in this paper, NFO has a fundamental static stability problem with respect to the location of the reference frame—i.e., if there is an error in the reference frame used for the control compared to the real reference frame position, this error will tend to increase if the machine is in prolonged regeneration. If the machine is motoring, the “natural” field orientation will result in a realignment of the errant reference frame.

A thesis by Glenberg [12] on sensorless control of induction machines considers issues of frame angle stability in NFO-based vector control under low speed operations. Glenberg concludes that there is a stability problem with voltage-driven NFO at low speeds, and this is exacerbated when there is poor knowledge of stator resistance.

Remark 4: The results presented in the current paper differ from Glenberg’s in that they specifically focus on NFO operating with current control in both axes, whereas Glenberg’s analysis centers on the voltage-driven NFO algorithm. The instability region in this paper differs from Glenberg’s. Furthermore, the current feeding leads to a different solution to the instability.

Remark 5: It should be noted that the stability problem being analyzed in this paper is a “static” stability problem. This term is being used to emphasize the fact that flux dynamics with respect to the forcing function of the stator $d$-axis current and the magnetizing current are neglected. Under conditions of control frame and real frame misalignment, the projection of the $d$ control axis input stator current onto the real $d$-axis changes with respect to time, which implies that there is a change of the magnetizing flux forcing current. However, if the angle difference between the control and real reference frames is considered to vary very slowly, then the derivative of the magnetizing current is very small and the approximation being made is reasonable.

A good analogy to this method of analysis is the static stability analysis of the induction machine steady state torque/slip characteristic in the area between peak torque slip and zero slip.
In this region of operation the machine is statically unstable with respect to small increases in the load torque.

In summary, the advantages of NFO compared to traditional voltage model flux estimation are as follows.

1) Due to the fact that the estimation is implemented in the estimated reference frame, reference frame errors tend to naturally realign (in motoring mode).

2) Since NFO does not use integration to calculate the flux, it does not suffer from integrator drift and initial condition problems.

3) The absence of the integrator means that NFO is less sensitive to errors in $R_s$.

4) NFO can operate successfully at low speeds.

This paper will concentrate on the NFO current-fed induction machine—i.e., both axes of the machine are driven by current sources. There is also a variant that uses a voltage drive in one axis of the machine and a current drive in the other axis, but this will not be considered here [4], [9].

The remainder of this paper is organized as follows. Section II outlines the frame stability problem both heuristically and analytically. Section II-B develops, analyzes and simulates a solution approach to the stability problem. Section III presents experimental results of NFO with and without the stabilization strategy applied. Finally, Section IV summarizes the conclusions that can be drawn from this paper.

II. NFO FRAME STABILITY PROBLEM

Before considering the formal analysis of the NFO frame alignment stability problem, it would be beneficial to heuristically consider the issue under motoring and generation (assuming a steady state condition).

The following discussion is with reference to Fig. 5. There are three axes on this figure—the $\alpha\beta$ axes are the axes for the stationary frame, the $dq$ axes are the axes for the estimated stator flux frame wherein the control is carried out (also known as the control frame), and finally the $xy$ axes align with the actual stator flux axis. The angular velocity of the true stator flux vector (i.e., $xy$ frame) is $\omega_{ms}$, whereas the angular velocity of the control frame is $\hat{\omega}_{ms}$.

From Fig. 2 one can see that the basic equations for NFO can be written as

$$\omega_{ms} = \frac{e_{sy}}{L_m |i_{ms}|} = \frac{e_{sy}}{|\psi_s|}$$  \hspace{1cm} (4)

$$\hat{\omega}_{ms} = \frac{e_{sq}}{L_m |i_{ms}|} = \frac{e_{sq}}{|\psi^*_s|}$$  \hspace{1cm} (5)

$$\tilde{\omega}_{ms} = \frac{\tilde{e}_{ms}}{|\psi^*_s|}$$  \hspace{1cm} (6)

and the estimated frame position is

$$\hat{\theta}_{ms} = \int \tilde{\omega}_{ms} \, dt + \hat{\theta}_{ms}(t = 0).$$  \hspace{1cm} (7)

The back EMF vector $\tilde{e}_{ms}$ is the back EMF produced if the reference flux in the machine is the actual flux in the machine. Therefore, $\tilde{\omega}_{ms}$ is the angular velocity of the reference frame if the flux in the machine is at the reference flux level of $|\psi^*_s|$.

If everything is precise and ideal then $\omega_{ms} = \hat{\omega}_{ms} = \tilde{\omega}_{ms}$, and $\hat{\theta}_{ms} = \theta_{ms}$ (the true frame position). However, if a frame error has occurred, then the situation of Fig. 5 may arise. In this particular case the control frame is ahead of the $xy$ frame.

Consequently, the projections of the currents will be incorrect on the true $xy$ frame.

Under the misalignment condition of Fig. 5 the actual back EMF $e_{ms}$ is less than $\tilde{e}_{ms}$ since the flux-producing current is the projection of $i^*_d$ as $i_{sx}$ onto the $xy$ axis. Therefore, $i_{sx} < i^*_d$ and $|\psi^*_s| < |\psi_{sx}|$. Consequently, the projection of $e_{ms}$ as $e_{sq}$ onto the $dq$ control axes means that $e_{eq}$ is even smaller than it would

Fig. 5. Space vector diagram of an induction machine under motoring mode.
otherwise be under correct alignment. This means from (5) that 
\( \hat{\omega}_{ms} \) is less than both \( \omega_{ms} \) and \( \tilde{\omega}_{ms} \), and therefore the \( dq \) frame will rotate slower than the exact frame would. Hence, under the integration of (7) the control frame will tend to approach the exact frame. This also means that the \( \theta_e \rightarrow 0 \) and the \( dq \) and \( xy \) frames approach each other.

**Remark 6:** Note that the \( xy \) frame does not necessarily rotate at the correct frame angular velocity \( \tilde{\omega}_{ms} \), but under this effect \( \omega_{ms} \rightarrow \tilde{\omega}_{ms} \) as well. Therefore, the \( xy \) and \( dq \) frames realign and the original misalignment is naturally corrected, hence the name of the frame alignment technique. The same argument applies if the \( \theta_e \) error is such that \( dq \) lags behind \( xy \), and for the other rotation direction.

Now consider the situation under regeneration. A similar argument can be mounted using Fig. 6, which shows the same situation as Fig. 5 except that the machine is regenerating. In this case the \( i_{sx} \) projection value is larger than the \( i_{sq}^* \) and hence \( |e_{ms}| > |\tilde{e}_{ms}| \), which results in

\[
\tilde{\omega}_{ms} = \frac{e_{sq}}{\tilde{\psi}_s} > \omega_{ms} = \frac{|e_{ms}|}{|\tilde{\psi}_s|}
\]  

(8)

that is, the \( dq \) frame will rotate faster than the \( xy \) frame under correct alignment. Under misalignment, the exact frame rotates at \( \omega_{ms} \) which is different from \( \tilde{\omega}_{ms} \), and two situations are possible. If \( \tilde{\omega}_{ms} < \omega_{ms} \) then regeneration is stable. If \( \tilde{\omega}_{ms} > \omega_{ms} \) (the more likely condition) then \( dq \) and \( xy \) frames in Fig. 6 will move apart—i.e., \( \theta_e \) will increase. Under typical conditions in regeneration mode the frame alignment error will grow and therefore the frame alignment is unstable.

To verify this instability, a number of simulation studies were carried out using the Saber simulation package. The simulations used the standard NFO algorithm with all parameters known and ideal currents sources to model a current controlled voltage source inverter. There was no switching in the simulation. Therefore, the simulation is very idealized. Fig. 7 shows one of these simulation results and illustrates the effect of frame instability in regeneration. Notice that NFO works correctly in motoring mode, but as soon as regeneration starts the frame alignment is lost and the torque output diverges from the correct value.

### A. Stability Analysis

To generate the operational quadrants where the frame alignment is stable and unstable, we shall consider the rate of change of the frame position error

\[
\frac{d\theta_e}{dt} = \dot{\omega}_{ms} - \omega_{ms}
\]  

(9)
where \( \theta_e = \theta_{ms} - \theta_{ms} \). For frame position stability, we shall see that we require \((1/\theta_e)(d\theta_e/dt) < 0\) (for \( \theta_e \neq 0 \)). To develop the expression, we utilize the fact that \( i_{sd}^* \) and \( i_{sq}^* \) are independent of the frame position (as can be deduced from Fig. 2).

Based on (4) and (5) one can write the following expression for \( \dot{\omega}_{ms} \):

\[
\dot{\omega}_{ms} = \frac{e_{sq}}{L_m |i_{ms}|} = \frac{e_{sg} \cos \theta_e}{|\psi_s^*|} = \frac{|\psi_s| \cos \theta_e}{|\psi_s^*|} \omega_{ms}. \tag{10}
\]

We can also write the following for the actual flux in the machine in terms of the reference currents:

\[
|\psi_s| = L_m |i_{ns}| = L_m i_{nx} = L_m \left( i_{sd}^* \cos \theta_e - i_{sq}^* \sin \theta_e \right). \tag{11}
\]

Using (10) and (11) we can write

\[
\dot{\omega}_{ms} = \left( \cos^2 \theta_e - \frac{i_{sq}^*}{i_{sd}^*} \sin \theta_e \cos \theta_e \right) \omega_{ms}. \tag{12}
\]

It is possible to manipulate the induction machine equations in a stator flux reference frame, ignoring the leakage inductance, into the following form [13]:

\[
L_m \frac{d|i_{ms}|}{dt} = R_r (i_{s}\psi_s - |i_{ms}|) - j(\omega_{ms} - \omega_r) |i_{ms}| L_m \tag{13}
\]

which can be separated into real and imaginary components to give

\[
L_m \frac{d|i_{ms}|}{dt} = R_r (i_{sx} - |i_{ms}|) \tag{14}
\]

\[
0 = R_r i_{sy} - (\omega_{ms} - \omega_r) |i_{ms}| L_m. \tag{15}
\]

Remark 7: Note from (14) one can see that if the stator flux is in steady state, the stator current is the stator magnetizing current of the machine. Equation (15) is very similar to the equivalent expression for FOC [14].
Using (15) and (11), as well as \( i_{sq} = i_{sd} \sin \theta_e + i_{sq}^* \cos \theta_e \), and substituting into (12) allows us to write

\[
\omega_{\text{ms}} = \frac{R_r \left( i_{sd}^* \sin \theta_e + i_{sq}^* \cos \theta_e \right)}{L_m \left( i_{sd}^* \cos \theta_e - i_{sq}^* \sin \theta_e \right)} + \omega_r. \tag{16}
\]

Substituting (12) and (16) into (9) (assuming no leakage) one can get

\[
\frac{d\theta_e}{dt} = \left( \frac{i_{sd}^* \cos \theta_e - i_{sq}^* \sin \theta_e}{i_{sd}^*} \right) \cos \theta_e \left( \frac{R_r \left( i_{sd}^* \sin \theta_e + i_{sq}^* \cos \theta_e \right)}{L_m \left( i_{sd}^* \cos \theta_e - i_{sq}^* \sin \theta_e \right)} + \omega_r \right). \tag{17}
\]

**Remark 8:** It is very difficult to gain any insight from (17) due to its highly nonlinear nature. Therefore, assuming \( \theta_e \approx 0.09 \text{ rad} \) (i.e., \( \approx 5^\circ \)), and that the flux and torque-producing current references are not near zero, the following approximations can be used to simplify the expression:

\[
\cos \theta_e \approx 1 \tag{18}
\]

\[
\sin \theta_e \approx \theta_e \tag{19}
\]

\[
i_{sd}^* i_{sq}^* \theta_e \ll (i_{sd}^*)^2 \text{ and } (i_{sq}^*)^2. \tag{20}
\]

Using the approximations in Remark 8 one can write (17) as

\[
\frac{d\theta_e}{dt} \approx - \left( \frac{R_r \left( i_{sd}^* \right)^2}{L_m i_{sd}^*} + \frac{\omega_r i_{sq}^* i_{sd}^*}{i_{sd}^*} \right) \theta_e \tag{21}
\]

which can be written as

\[
\frac{d\theta_e}{dt} = - \left( \frac{1}{T_{\text{rm}}} x^2 + \omega_r x \right) \theta_e = -x \left( \frac{1}{T_{\text{rm}}} x + \omega_r \right) \theta_e \tag{22}
\]

where \( x = i_{sq}^*/i_{sd}^* \) and \( T_{\text{rm}} = L_m / R_r \).

For stability we require that the \( \frac{d\theta_e}{dt} \) term has a sign which indicates that the error time gradient is driving \( \theta_e \) toward zero. Dividing both sides of (22) by \( \theta_e \) gives \((1/\theta_e)(d\theta_e/dt) < 0\) (under the condition that \( \theta_e \neq 0 \)), which means that the \( \theta_e \) error is approaching zero. From (22) this condition implies

\[
x \left( \frac{1}{T_{\text{rm}}} x + \omega_r \right) > 0 \tag{23}
\]

or

\[
\text{sign}(x) = \text{sign} \left( \frac{1}{T_{\text{rm}}} x + \omega_r \right). \tag{24}
\]

In motoring mode with \( x > 0 \) (assuming \( \omega_r > 0 \)), then (24) is always satisfied. Therefore, motoring is always stable and supports the previous heuristic reasoning.

Now consider regeneration. In this case (again assuming \( \omega_r > 0 \)), with \( x < 0 \) (since \( i_{sq}^* < 0 \) to give negative torque), then

\[
\frac{1}{T_{\text{rm}}} x + \omega_r < 0 \Rightarrow x < -\omega_r T_{\text{rm}} \tag{25}
\]

for (24) to be satisfied.

If the stability regions for both motoring and regeneration are plotted on a \( \omega_r \text{ versus } x \) plot, then Fig. 8 results. The unstable regions are a significant part of the operational envelope in regeneration mode.

The results for both motoring and regeneration are tabulated in Table I. The hatched (stable regeneration) and crosshatched...
TABLE I
SUMMARY OF STABILITY BOUNDARY CONDITIONS FOR MOTIONING AND GENERATING

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\omega_T)</th>
<th>(i_{sq}^<em>/i_{sd}^</em>(x))</th>
<th>(\theta_e)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motoring</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>(x &gt; -\omega_T T_{rm})</td>
</tr>
<tr>
<td></td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>(x &gt; -\omega_T T_{rm})</td>
</tr>
<tr>
<td></td>
<td>&lt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>(x &lt; -\omega_T T_{rm})</td>
</tr>
<tr>
<td>Generating</td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>(x &lt; -\omega_T T_{rm})</td>
</tr>
<tr>
<td></td>
<td>&gt; 0</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
<td>(x &lt; -\omega_T T_{rm})</td>
</tr>
<tr>
<td></td>
<td>&lt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>(x &gt; -\omega_T T_{rm})</td>
</tr>
</tbody>
</table>

TABLE II
INDUCTION MACHINE PARAMETERS OF THE EXPERIMENTAL MACHINE, AND USED IN THE SIMULATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetizing inductance (L_m)</td>
<td>0.0961 H</td>
</tr>
<tr>
<td>Leakage inductance (L_{1a}, L_{1r})</td>
<td>0.0041 H</td>
</tr>
<tr>
<td>Rotor resistance (R_r)</td>
<td>0.652</td>
</tr>
<tr>
<td>Stator resistance (R_s)</td>
<td>0.651</td>
</tr>
<tr>
<td>Pole pairs (p_p)</td>
<td>2</td>
</tr>
</tbody>
</table>

(stable motoring) areas in Fig. 8 correspond to the areas that satisfy both the \(x\) criterion and the “Condition” criterion in Table I. For example, when motoring with \(\omega_T > 0\) and \(\theta_e > 0\), then the region where \(d\theta_e/dt < 0\) is where the regions defined by \(x > 0\) and \(x > -\omega_T T_{rm}\) overlap—i.e., the first quadrant in Fig. 8. Similar arguments can be made for other areas in Fig. 8.

To check the validity of the linearized analysis, the full nonlinear expression (17) was plotted using a 3-D plotting tool. The machine parameters used are the same as those for the experimental machine and appear in Table II. Two cases were plotted—one for motoring and one for regeneration, and these appear in Figs. 9 and 10, respectively. Note that the plots are at one speed only—75 mechanical rad/s (i.e., 150 electrical rad/s), this being representative of the results at other speeds.

Remark 9: Static frame stability can be easily seen from the 3-D plots by realizing that frame stability corresponds to \(\text{sign}(\omega_T) = -\text{sign}(\theta_e)\). Therefore, if the frame misalignment \(\theta_e\) is positive, then for static stability the condition \((d\theta_e/dt) < 0\) must hold. If this condition is not satisfied, then there is static frame instability.

In Fig. 9 (for motoring operation) one can see based on the reasoning in Remark 9, for small \(x\) (i.e., small torques) and \(\theta_e < 0\) that \(d\theta_e/dt < 0\), the NFO frame will move away from the real frame. The range of \(i_{sq}^*/i_{sd}^*\) values for which this occurs can be seen from the accompanying contour plot. This statically unstable region did not show up in the linearized analysis. Therefore, there are conditions where NFO displays static frame position instability even when motoring.

As predicted from the linearized analysis, examination of Fig. 10 for regeneration shows that the frame alignment is statically unstable in most regions of operation. There is a similarity with the motoring case in that at very low torques (i.e., \(i_{sq}^*/i_{sd}^*\) small under nominal flux conditions) the regeneration mode is stable for \(\theta_e > 0\).

Remark 10: Figs. 9 and 10 indicate that the linearized analysis is broadly representative of the performance of the system when leakage inductance effects are ignored in the machine.

Remark 11: The analysis in this paper has ignored leakage inductance. If leakage inductance is included, then cross coupling develops between the axes, and a decoupling network needs to be added [14]. When this is done (and even if it is not), the frame static stability results are virtually the same as those for the no leakage case [4], [15].

B. Stabilization Strategy

Equation (26) can be used for stability analysis similar to that for uncompensated NFO. Due to the similarity of the manipulations to the previous ones, we shall simply present the resulting expression [13]

\[
\dot{\theta}_e = \frac{d\theta_e}{dt} = \frac{e_{sq} - \text{sign}(e_{sq})k e_{sd}}{i_{sd}^*} \tag{26}
\]

where \(k\) is included as a tunable gain parameter.

Equation (26) can be used for stability analysis similar to that for uncompensated NFO. Due to the similarity of the manipulations to the previous ones, we shall simply present the resulting expression [13]

\[
\dot{\theta}_e = \frac{d\theta_e}{dt} = \frac{e_{sq} - \text{sign}(e_{sq})k e_{sd}}{i_{sd}^*} \tag{26}
\]

which can be simplified using similar approximations as those of Remark 8 to

\[
\dot{\theta}_e = \frac{d\theta_e}{dt} \approx -\left(\frac{i_{sq}^*}{i_{sd}^*} + \text{sign}(e_{sq})k\right)\left(\frac{R_r i_{sq}^*}{L_m} + \omega_r\right) \theta_e \tag{28}
\]

which can be written as (with \(x\) and \(T_{rm}\) as defined previously)

\[
\dot{\theta}_e = \frac{d\theta_e}{dt} \approx -\left(\text{sign}(e_{sq})k + x\right)\left(\frac{1}{T_{rm}} + \omega_r\right) \theta_e \tag{29}
\]

Remark 12: Note that if \(k = 0\) in (29), then the expression collapses to (22).

If similar logic is applied to (29) as done with (22), then the stable and unstable areas of Fig. 11 result.

Remark 13: One can see from Fig. 11 that the unstable regions have not been completely eliminated. However, they have been substantially decreased. Furthermore, by dynamically changing the feedback term \(k\) one can change the size and location of the stable/unstable regions.

As with the unaugmented NFO case, the full nonlinear expression represented by (27) has been plotted for both the motoring and regeneration cases. The feedback gain used in
Fig. 9. Plot of (17) for motoring, $\omega_r = 150$ elec. r/s (no leakage).

Fig. 10. Plot of (17) for regeneration, $\omega_r = 150$ elec. r/s (no leakage).

these plots is $k = 1$. As with previous similar plots the angular velocity of the machine is arbitrarily chosen to be 75 mechanical rad/s (which is also representative of what happens at other speeds).

Fig. 12 shows the situation when motoring. One can see that the whole motoring region is now stable, and the area of static instability for $\theta_e < 0$ and $x = i_{sq}^* / i_{sd}^*$ small, observed in the nonfeedback case shown in Fig. 9, is no longer present.

Fig. 13 is the plot of $d\omega_e/dt$ for regeneration with the feedback augmentation. The plot in this case is somewhat more complex than the motoring plot. One can see that for $\theta_e > 0$ the feedback has made NFO static stable under regeneration. For $\theta_e < 0$ though, there are areas of stability and instability. As $x = i_{sq}^* / i_{sd}^*$ increases (which for nominal flux levels means at higher torque levels), the algorithm is still statically unstable.

**Remark 14:** The results shown in Fig. 13 align with the linearized analysis shown in Fig. 11—there is an area of instability at higher values of $x$.

It is interesting to consider whether the aforementioned static instability remains if the feedback gain is increased. The situation under regeneration with $k = 2$ is shown in Fig. 14. The area of static instability when $\theta_e < 0$ has decreased substantially, but has not been eliminated at higher torque levels (for nominal flux).
Remark 15: If the feedback gain $k$ is increased, it is possible to eliminate the instability under regeneration. However, high gains will mean that noise on the $e_{sd}$ value will feed into the frame angular velocity estimate.

Simulation studies were conducted using the proposed stabilization strategy. Fig. 15 is representative of the results obtained. The previously unstable regeneration region is now stable, and the torque performance of the system is excellent.

Remark 16: Note in Fig. 15 that $e_{sd} \neq 0$, but very small relative to the value of $e_{eq}$ at the high shaft angular velocities in the simulation, indicating that there is good frame alignment.

Remark 17: During the simulation studies it was observed that even the augmented NFO algorithm could still tend to misalign, particularly when rapid and large torque transients were requested.

III. EXPERIMENTAL RESULTS

The experiments were carried out using a 38 kW insulated-gate-bipolar-transistor-based inverter connected to a 7.5 kW wye-connected induction machine. The machine parameters appear in Table II. This machine was mounted on a
dynamometer test bed with a dc load machine configured as a simple Ward–Leonard system to provide static loading capable of regeneration or motoring operation.

The software used for the tests was a modification of existing software that implemented either FOC or instantaneous power control algorithms. Therefore, the underlying code for current control, sampling, and basic timing could all be used. Only minor modifications were required for the NFO algorithm.

The code itself was written in “C” and executed in a TMS320C6701 floating-point DSP. The control frequency was 3906.25 Hz, corresponding to a control period of 256 μs. Symmetrical pulsewidth modulation was used, and so there was current sampling at the beginning and middle of each of the control intervals. The software was designed with an integrated data logging system that allowed both internal control variables as well as sampled currents, voltages, and shaft speeds to be logged. The number of simultaneous variables that can be logged depends on the size of the logging buffers, and in most circumstances approximately four variables can be simultaneously logged for approximately 3 s for each variable. It is possible to trigger logging at a particular time, or to continuously log into a circular buffer.

Both the normal (or basic) NFO algorithm, as well as the proposed augmented NFO algorithm, were implemented on
the experimental system. Fig. 16 shows the structure of the algorithm for the normal NFO with a proportional–integral speed control loop around it. Similarly, the diagram for the augmented NFO controller appears in Fig. 17.

A. Startup and Steady-State Tests

First, both basic \((k = 0)\) and augmented \((k = 1)\) NFO algorithms were tested for startup. After allowing 0.512 s for fluxing the machine, a step from 0 to 50 rad/s of the angular velocity reference was applied. This is close to 1/3 of the rated motor speed. After 1.792 s, a second step from 50 to 100 rad/s was requested. Both steps were applied for a long enough time for the machine to come to steady state, so that both transient and steady state performance of the algorithm could be evaluated using the same plots. Note that the reference magnetizing current \(i_{s_q}^*\) was always constant and equal to 10 A.

Due to the size limitations of the logging buffer, the same experiment was repeated twice for each case. In the first experiment the following parameters were recorded: angular velocity, reference and actual electromagnetic torque, as well as the angular error between the true position of the stator flux vector and that assumed by NFO. The angular velocity measurements were taken from the output of a velocity observer that used readings from a position encoder to give smooth angular velocity estimates. The torque reference values taken from the output of the speed control loop were those used by NFO algorithm to calculate its \(i_{s_q}^*\) values. Actual electromagnetic torque could not be directly measured and instead was estimated using a torque estimator, which was a part of the previously mentioned FOC algorithm. This FOC algorithm has been extensively tested with the same machine and proved to provide good control and high precision results. In our case FOC worked in the background, generating its own independent estimates of the main control parameters.

The same FOC algorithm calculated the magnitude and angular position of the rotor flux vector. Those two factors, together with the stator currents and the known machine parameters, were used to estimate the stator flux magnitude and angular position. This independent estimate of the stator flux position was considered to be the “actual” position as opposed to that estimated by NFO. Comparison between the two gave us the angular error of the NFO control frame. Note that it cannot be taken for granted that the estimated angular error is the result of the NFO algorithm inaccuracy only, but we are assuming that NFO is the primary contributor to this angular error.
The first set of the startup plots for NFO with \( k = 0 \) and \( k = 1 \) are shown in Figs. 18 and 19, respectively. By comparing these figures one can appreciate that with the additional feedback applied, the precision of the speed control, the torque waveforms and the accuracy of the NFO control frame position significantly improved. However, for both \( k = 0 \) and \( k = 1 \) the startup from zero speed was somewhat problematic. Original frame misalignment reached almost \(-\pi\) in both cases and then gradually ended with small values. “Actual” (i.e., estimated by FOC) torque was negative at the start and then moved toward positive reference torque values. Issues related to startup of SFO-related algorithms are not new [16], and in relation to NFO this can be undoubtedly improved with careful redesign of the startup initialization of the algorithm.

The second step, from 50 to 100 rad/s, was much smoother in both cases. Comparison of the second step in Fig. 18 to that in Fig. 19 clearly demonstrates the improved performance of the augmented NFO over the basic NFO.

After approximately 3 s, the plots in Figs. 18 and 19 evolve into steady state. For \( k = 0 \) the frame misalignment at the end averaged 10.7° while for \( k = 1 \) it was only \(-2.6°\). In both cases actual torque in steady state was near zero. But for NFO with \( k = 0 \) this corresponded to the negative reference torque of \(-2.95 \text{ N} \cdot \text{m}\) due to the frame misalignment. For \( k = 1 \) the corresponding reference torque value was 0.10 N \cdot m.

In the repeat of the same experiment, the stator and the rotor flux magnitudes together with the \( e_{sd} \) values were recorded. The \( d \)-axis flux voltage \( e_{sd} \) was that estimated in the NFO control frame. The rotor and the stator flux magnitudes were estimated by the FOC algorithm and were assumed to be “true” values. The results for \( k = 0 \) and \( k = 1 \) are shown in Figs. 20 and 21. In both cases, the flux magnitudes had substantial swings in the negative direction when starting from zero speed. After the startup problems were overcome, much smaller flux perturbations were observed for \( k = 1 \) compared to those for \( k = 0 \).

As previously explained, fluctuations of the direct-axis flux voltage \( e_{sd} \) are correlated with the frame angular error. For \( k = 0 \) these fluctuations were as large as \( \pm 20 \text{ V} \), and the final value of \( e_{sd} \) in steady state was more than 50 V. For \( k = 1 \), as a direct consequence of the stabilization feedback, the \( e_{sd} \) voltage was near zero. It was also observed that with increasing \( k \) value, the \( e_{sd} \) signal was becoming noisier, particularly at higher speeds.

### B. Torque Step Change Test

To further confirm the effect of the stabilization strategy and the validity of the simulation results of Fig. 15, a torque step change was applied to the NFO-controlled machine, first with \( k = 0 \) and then with \( k = 1 \). The outer speed control loop was
disabled. After the machine was fluxed, a step change from 0 to 20 N·m of the reference torque value was applied. This is approximately 2/3 of the rated torque value of the machine. After 1.536 s another step change from 20 to −5 N·m of the reference torque followed. The angular velocity, actual torque and angular error of the stator vector position were estimated and recorded in the same way as described in Section III-A.

The experimental plots shown in Fig. 22 were obtained for \( k = 0 \) and corresponded to the simulation plots of Fig. 7. One can see from Fig. 22 that NFO with \( k = 0 \) was able to approximately follow the positive torque reference. Once the torque reference changed its sign, the basic NFO algorithm completely lost control over the machine. This manifested itself in uncontrolled speed, huge torque fluctuations and multiple turns of the angular error. The observed behavior corresponds well with the simulation results of Fig. 7, considering that the simulations are for an ideal system (i.e., the current controlled inverter is modeled by ideal current sources and all parameters are exactly known).

Under the same conditions NFO with \( k = 1 \) was able to successfully control the machine. This can be seen from Fig. 23, which corresponds to the simulation results of Fig. 15. Even though it had a higher initial frame misalignment, the algorithm was able to self-align its frame and provide good tracking of the reference torque under both positive and negative torque steps. However, further experiments showed that with steps into higher negative torque values the augmented NFO algorithm also experienced instability problems. This is further discussed in the next section.

C. Test for the Regeneration Limit in Steady State

It was expected from the previously presented theoretical analysis and the 3-D plot of Fig. 13 that even the augmented NFO would lose frame stability under certain conditions related to combinations of torque and rotor speed values. The following test was done for NFO with \( k = 0, k = 1 \) and \( k = 2 \) to investigate this issue. The test machine with the NFO control was loaded by a dc machine controlled by a Ward–Leonard system. The test machine was run at a constant speed of 75 rad/s (mechanical). The dc machine was run as a generator applying negative torque to the test machine. This negative torque was...
Fig. 18. Startup plots for NFO with $k = 0$.

Fig. 19. Startup plots for NFO with $k = 1$. 
slowly increased up to the point when the test machine would lose its stability.

The test showed that NFO with \( k = 0 \) was not able to regenerate at all under the above conditions. The control algorithm would lose its stability immediately after crossing the zero torque margin. The corresponding plots were very similar to those shown in Fig. 22 and are not presented here. With \( k > 0 \) the NFO algorithm was able to work in regeneration mode. With \( k = 1 \) the maximum negative torque that it was able to produce under the above stated conditions was \(-12 \text{ N} \cdot \text{m}\), with \( k = 2 \) the limit was \(-16 \text{ N} \cdot \text{m}\). Fig. 24 shows the torque limit for \( k = 2 \) case. These results confirm the conclusions drawn from Figs. 13 and 14.

**Remark 18:** The experiments showed that additional stabilization feedback enabled the NFO algorithm to work in regeneration mode over part of the torque region (16 \text{ N} \cdot \text{m} is approximately half of the rated torque of the machine). Higher feedback gains could solve this problem, but would require filtering of the \( e_{sd} \) values to eliminate the noise evident in Figs. 20 and 21. The ability of the algorithm to work stably under dynamic torque conditions would also be significantly improved by applying the higher gain stabilization feedback.
Fig. 22. Torque step change test NFO with $k = 0$.

Fig. 23. Torque step change test NFO with $k = 1$. 
IV. CONCLUSION

The main conclusions that can be drawn from this paper are as follows.

1) The NFO algorithm does not have the low speed voltage integrator initialization and drift problems of traditional voltage model SFO algorithms. The lack of a voltage integrator for the flux makes the algorithm more robust to errors in the stator resistance.

2) The “normal” NFO algorithm has a frame angle static instability for most of the regeneration region. This has been proven using linearized analysis, and also from nonlinear 3-D plots of $d\theta_e/dt$.

3) The regeneration mode of operation can be made statically stable by augmenting the basic NFO algorithm with $\text{sign}(e_{sq}) \times e_{sd}$ feedback. This has been proven to eliminate the static frame instability identified in the basic algorithm.

4) Larger feedback gains would be able to stabilize NFO over the whole regeneration operational range. However, issues associated with noisy feedback measurements with the higher gain must be addressed if higher gains are used.

5) The results of the analysis and simulation for both the basic and augmented NFO algorithms have been confirmed by experimental results. The experimental results confirm that with augmentation NFO is capable of sustaining both motoring and regeneration with “natural” field orientation still occurring.

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BETZ AND MIRZAEVA: FRAME ALIGNMENT STABILITY ISSUES IN NATURAL FIELD ORIENTATION

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