Natural Field Orientation Concept: a Tutorial

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Abstract—Natural Field Orientation (NFO) is a technique for generating a rotating reference frame position for an induction machine which is 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. This paper presents a tutorial on the different forms of NFO and their various merits and deficiencies relative to each other. In addition it also examines the relationship between NFO and stator flux orientation (SFO). It briefly examines frame alignment stability issues in both NFO and SFO, highlighting the essential differences in the performance. Finally, a rotor flux NFO version is developed and compared to the stator flux oriented NFO. The discussions are backed up by simulation and experimental results where appropriate.

NOMENCLATURE

R_s, R_r - stator and rotor resistances;
 L_m, L_s, L_r - magnetising, stator and rotor inductances;
 σ - leakage coefficient, $\sigma = 1 - L_m^2/(L_s L_r)$;
 (x, y) - axes of the frame aligned with the actual position of the stator flux vector. The x axis is aligned with the stator flux vector;
 (d, q) - control frame aligned with the estimated position of the stator flux vector;
 u_{sx}, u_{sy} - stator voltage vector projections onto (x, y) axes. Similarly for stator current i and back-emf e vectors;
 u_{sd}, u_{sq} - stator voltage vector projections onto (d, q) axes. Similarly for stator current i and back-emf e vectors;
 $|\underline{i}_{ms}|, |\underline{\psi}_s|$ - magnitudes of stator flux and stator magnetising current;
 $|\underline{i}_{mr}|, |\underline{\psi}_r|$ - magnitudes of rotor flux and rotor magnetising current;
 $\underline{u}_{s\psi s}$ - the stator voltage space vector in a stator flux frame;
 $\underline{i}_{s\psi s}$ - the stator current space vector in a stator flux frame;
 $|\underline{\psi}_s^*|$ - reference value of the stator flux magnitude. Similarly, * denotes reference values for other quantities;
 ω_{ms}, ω_{mr} - angular velocities of stator flux and rotor flux vectors;
 ω_r - shaft angular velocity (elec. rad/sec).

I. INTRODUCTION

Natural Field Orientation (NFO) concept was first introduced and patented in the 1980s [1]. In its original version it was closely related to stator flux orientation (SFO). Some authors, for example, in [2, 3] refer to it as a simplified open loop method of SFO control. Simplification comes from the fact that the stator flux vector is not estimated but assumed to be at its reference value. Since the NFO algorithm uses the reference flux, it does not have to carry out problematic integrations to find out the correct flux. Assuming that the flux is at a constant value, the stator flux vector will be 90° spatially lagging the stator flux voltage and can be easily obtained if this voltage is accurately measured.

One of the important properties of SFO is that there is a natural tendency for a misaligned control frame (i.e. when the control frame is not aligned with the stator flux) to implicitly realign. The assumption that the stator flux is at the reference value, which is the fundamental difference between NFO and SFO, *does not* affect the inheritance of the realignment property from SFO to NFO [4]. This interesting property of NFO together with other positive features like low parameter sensitivity justify more detailed examination of the relative merits of NFO versus SFO.

The remainder of this paper will consider a family of control techniques, broadly grouped under the umbrella of NFO, with the common feature that the flux magnitude is assumed to be equal to its reference value. Apart from obvious sensor and sensorless options, the NFO family includes current-fed, voltage-fed or mixed (current-fed on one axis and voltage-fed on the other) modifications, as well as stator flux or rotor flux oriented variants. The remainder of this paper will present a brief tutorial on the NFO family of control strategies. Section II will review the raw NFO concept and present some of the key equations. Section III will consider some of the differences between the closely related SFO and NFO. Special emphasis will be placed on issues associated with parameter robustness differences between the two algorithms. Section IV will consider the implications of current fed and voltage fed variants of NFO. Section V will consider the implications of stator flux oriented NFO versus rotor flux oriented NFO. Finally, Section VI will present some conclusions and observations about the NFO algorithm, especially with reference to SFO.

II. RAW NFO CONCEPT

In the original patents [1, 5] the NFO concept was described as a way of transforming an induction machine into an equivalent voltage fed DC machine, where the voltage on one axis controlled the field and the voltage on the other axis the torque producing current. This way of viewing the NFO concept can be easily developed directly from the stator voltage equation of an induction machine:

$$\underline{u}_{s\psi s} = R_s \underline{i}_{s\psi s} + L_m \frac{d}{dt} |\underline{i}_{ms}| + j\omega_{ms} L_m |\underline{i}_{ms}| \quad (1)$$

Breaking (1) into real and imaginary parts gives:

$$u_{sx} = R_s i_{sx} + L_m \frac{d|\underline{i}_{ms}|}{dt} \quad (2)$$

$$u_{sy} = R_s i_{sy} + \omega_{ms} L_m |\underline{i}_{ms}| \quad (3)$$

Equations (2) and (3) are very close to the equations for a separately excited DC machine with compensating windings – using standard notation these can be written as:

$$u_f = R_f i_f + L_f \frac{di_f}{dt} \quad (\text{the field equation}) \quad (4)$$

$$u_a = R_a i_a + \omega_r L_f i_f \quad (\text{the armature equation}) \quad (5)$$

Fig. 1: Raw NFO algorithm that converts an induction machine into a virtual voltage fed DC machine.

The key difference between field equation (2) as compared to (4) is that $|\dot{i}_{ms}|$ is a function of not only the i_{sx} current but also of the rotor conditions and i_{sy} (via cross-coupling effects). These various parameters are reflected in the flux of the machine via the expression $\psi_s = \int e_{sx} dt = \int (u_{sx} - R_s i_{sx}) dt$. Therefore if the machine is voltage driven and if the i_{sx} component of current is measured and the stator resistance R_s is accurately known, then a u_{sx} voltage can be determined so that the desired value of $|\dot{i}_{ms}|$, and therefore flux, is obtained in the machine.

If one then applies the NFO concept we have that:

$$\omega_{ms} = \frac{u_{sy} - R_s i_{sy}}{L_m |\dot{i}_{ms}^*|} = \frac{e_{sy}}{|\psi_s^*|} \quad (6)$$

where $|\dot{i}_{ms}^*|$ and $|\psi_s^*|$ denote the reference values for these quantities and not their actual values. Another observation is that in steady state, when $d|\dot{i}_{ms}|/dt = 0$ the back-emf voltage $e_{sx} = u_{sx} - R_s i_{sx}$ should equal zero. Figure 1 shows the structure of the raw NFO algorithm more or less as it appeared in the original patents.

III. NFO VERSUS TRADITIONAL SFO

As mentioned in the introduction, NFO is a special form of the traditional SFO algorithm. The main difference between the SFO and NFO techniques is shown in Figures 2a and 2b respectively. These diagrams show the relevant parts of the SFO and NFO algorithms related to the generation of the stator flux vector position in the machine. One can see that NFO has no integration to determine the flux of the machine, while with SFO an estimate of the stator flux magnitude is obtained by integrating the e_{sx} component of the stator voltage vector.

One obvious and significant advantage of NFO, as compared to SFO, is its improved frame angle robustness to inaccurate knowledge of the stator resistance. In SFO if the stator resistance has, for example, a lower value in the controller than the true value in the machine, then the e_{ds} voltage will be zero under “steady state” but the true e_{sx} back-emf within the machine will be non-zero. Consequently the flux in the machine will be building up, undetected by the control algorithm. This will result in a tendency for the calculated frame angular velocity to increase since the e_{sy} value will increase, but the estimated flux magnitude will remain the same. Fortunately, under current fed control strategies, the effect will stabilise at some significant non-zero frame misalignment angle when the flux producing current will be low enough to compensate for these other effects.

(a) Traditional stator flux orientation

(b) Natural field orientation

Fig. 2: Comparison between traditional SFO and NFO (both current fed, leakage is ignored).

Errors in the stator resistance will also have an effect on NFO. However, since we are *not* integrating the flux producing back-emf the precise phenomena described above does not occur. In this case the e_{sy} voltage will be in error because of the resistance error. However, if the machine is operating at a reasonable speed the relative error due to this will be small, and consequently the frame misalignment will be small. In addition to this, for a current fed machine, the error in the frame position is such that it will make the value of e_{sy} change in a fashion to prevent any accumulation of the frame error [6–8]. This conclusion is supported by the results of the current-fed NFO simulations that appear in Figure 3. These figures show the results of a simulation where the induction machine is operating as a NFO controlled torque source (i.e. no speed or position feedback). In the first case the correct R_s value is used by the algorithm. In the second case an error of more than 25% is introduced in R_s . One can see that performance of the algorithm is only marginally worse in the second case than in the first, which indicates that the frame position is not grossly in error [6].

Figure 4 shows simulation and experimental results for the raw (unaugmented) NFO algorithm with 50% R_s error. The NFO algorithm has a speed controller around it, and the desired speed is a simple step. The simulation in this case was very accurate and included the inverter dead-time. One can see that the experimental and simulation results are very close, and that a static e_{sd} voltage appears indicating a static frame misalignment to compensate for the R_s error. Numerous other experiments have been carried out which confirm the robustness of NFO with respect to R_s error [6–8].

Similar Figure 5 shows the performance of SFO under the same parameter inaccuracy in R_s , and with all other parameters known exactly. The algorithm in implemented open

(a) Correct value: $R_s = 0.435\Omega$

(b) Erroneous value: $R_s = 0.55\Omega$

Fig. 3: Simulation of the current fed NFO algorithm.

loop (i.e. without a flux feedback path), so that the situation is equivalent to the conditions under which the NFO algorithm was operating. As can be seen, the error in the stator resistance leads to totally unacceptable torque performance in the SFO algorithm. Similar results are obtained if there is a flux feedback loop with SFO.

Whilst SFO is more susceptible to frame misalignment from inaccurate R_s knowledge as compared to NFO, SFO has the advantage that it does not have the same problem with unstable frame alignment in regeneration [4, 6, 7]. The NFO algorithm in its original form demonstrates static frame alignment instability over virtually the whole regeneration region. This means that under regeneration any error in the NFO control frame position will tend to lead to an increase in the error. For example, if the control frame moves ahead of the correct frame position, then under certain conditions the e_{sy} value can become larger than it should be under perfect alignment. This results in the ω_{ms} estimated in equation (6) being larger than the correct angular velocity value, and consequently the control frame will move further away from the “true” frame position. This clearly will lead to unacceptable performance. A simulation of the “raw” NFO algorithm in motoring and regeneration is shown in Figure 6. It shows that the machines performance is excellent under motoring, but when the torque reference

(a) Simulation data

(b) Experimental data

Fig. 4: NFO test: Unaugmented, $\Delta R_s = +50\%R_s$, L_m correct

becomes negative the machine torque initially follows it, but then collapses to zero as the control frame slides away from the true frame position.

The frame instability and misalignment can be corrected by augmenting (6) using the e_{sd} value as follows [4, 6]:

$$\omega_{ms} = \frac{e_{sq} - k[\text{sign}(e_{sq})e_{sd}]}{|\psi_s^*|} \quad (7)$$

where k is a tunable control parameter. Figure 7 shows the performance of NFO using this approach. Extensive simulation experimental results show that this augmentation makes the algorithm more robust to parameter errors.

Let us consider SFO under regeneration. The dq frame is assumed to be ahead of the xy frame, which means that the angular velocity of the dq frame is higher than the xy frame. Assuming a current fed machine, the frame misalignment results in an increase in the e_{sd} (away from the ideal zero value). This voltage is integrated to calculate an estimate of the flux, which is used in equation (6) (in place of the reference flux). The value of e_{sq} is a projection of e_{sy} , and therefore is less than e_{sy} . Furthermore, the projection of i_{sd} onto the x axis is also less, and this means that the actual flux magnitude will decrease from the desired flux. The net result of all these influences is that the new value of the dq frame angular velocity will decrease. The feedback effect of the stator flux estimate is strong enough to force the angle error between the two frames

(a) Correct value: $R_s = 0.435\Omega$

(b) Erroneous value: $R_s = 0.55\Omega$

Fig. 5: Simulation of current fed SFO algorithm.

to zero. Figure 8 shows the performance of SFO under similar conditions to those shown for NFO in Figure 6. The parameters of the machine used in the SFO controller are the true machine parameters in this example. As can be seen SFO performs very well in both motoring and regeneration modes.

Remark 1: It turns out the SFO benefits substantially by the use of e_{sd} feedback augmentation [6].

Whilst NFO is robust, relative to SFO, with respect to R_s errors, it is more susceptible to errors in L_m . Errors in L_m again lead to errors in the flux produced in the machine because the reference current is calculated using the L_m value as shown in Figure 2b. A lower reference current results in a lower e_{sy} value which in turn feeds around to the algorithm via $\underline{e}_{ms}$. It can be shown [6, 8] that NFO can tolerate $\pm 15\%$ errors in the L_m and still work satisfactorily. Fortunately standard machine parameter tests are able to satisfy this accuracy in this parameter. SFO on the other hand in its practical implementation, tends not to be as sensitive to L_m error. Because an estimate of the actual flux, calculated by voltage integration, is available in this algorithm, then a feedback loop can be simply implemented to correct flux errors. This process of course, is precisely why the algorithm is sensitive to R_s .

Inverter dead-time can also have an influence on the performance of NFO since it affects the accuracy of the determination of the machine back-emf. It can be shown that the effect of dead-time is very similar to resistance error, and results in a misalignment of the control frame with respect to the true stator flux frame. Investigation of the influence of dead-time has shown that the robustness of the NFO to its effects is similar

Fig. 6: Stator flux oriented NFO for motoring and regeneration.

Fig. 7: NFO simulation with $k = 1$ with e_{sd} feedback.

to its robustness with respect to stator resistance error.

Summary 1: The following interim observations can be made:

- NFO is essentially an alternative form of SFO.
- NFO has the disadvantage that it is statically unstable with respect to frame alignment in regeneration.
- Because NFO does not use integration to estimate the stator flux, it is particularly robust with respect to errors in the stator resistance and applied voltage errors due to dead-time effects. This also means that it can operate at lower speeds as compared to the traditional SFO algorithm.
- NFO is more sensitive to L_m error than SFO, but the level of sensitivity is not high and is not an impairment to practical implementation.

♦ *Remark 2:* Note that orientation of NFO to the stator flux vector brings the same limitations as traditional vector control aligned to this frame, namely that there is effectively a static torque overload limit caused by the machine effectively slipping over the top of the torque slip characteristic [9]. ♦

IV. I-I, V-I AND V-V IMPLEMENTATIONS OF NFO

Equations (2) and (3) suggest several alternative control topologies. So far we have considered the strategy that uses current control on each axis of the machine (we shall denote this as i-i control). This is the same control scheme used by

Fig. 8: Simulation of SFO under motoring and regeneration conditions.

most field oriented vector controllers. A block diagram of the i-i control with stator flux oriented NFO appears in Figure 9a. It is implemented by using current control loops around both flux producing and torque producing axes of the machine. Effectively the machine is being driven by current sources. Two other alternatives are to use voltage control on both axes (denoted as v-v control), or current control on one axis and voltage control on the other (denoted as v-i control). NFO with v-v control was suggested in [1, 2, 5, 10] and NFO with v-i control in [11].

In v-i control it is natural to use voltage control on the flux producing axis of the machine since flux and voltage are related via Faraday's Law, and current control on the torque axis since torque is related to the current magnitude orthogonal to the flux vector. A block diagram of the v-i control used in the simulations is shown in Figure 10a. To simulate v-v control one can use the same scheme after removing the explicit control loop around the current (the torque loop).

Both v-v and v-i schemes showed reasonable performance when the R_s value was precisely known. However, with the same erroneous R_s value as that used in the simulation of the i-i NFO (see Figure 3b), both v-i and v-v control schemes were found to be completely unusable. Simulation results for the v-i NFO under this condition appear in Figure 10b.

Remark 3: In the i-i driven case we are applying current in such a manner that $i_{sd} = i_{sd}^*$. Then we measure voltage u_{sd} and estimate $e_{sd} = u_{sd} - R_s i_{sd}$. If there are errors in R_s which cause the control frame misalignment, a non-zero value of the e_{sd} would clearly indicate this misalignment. Indeed the presence of e_{sd} will detect misalignment regardless of the cause. This can be used to compensate for it by applying, for example, an additional stabilisation loop based on the e_{sd} signal. This idea will be explored in depth in a companion paper [12]. ♦

Remark 4: In the v-i/v-v situation if misalignment occurs (for whatever reason) there is no indication of this via the e_{sd} voltage – since we are applying u_{sd} in such a manner that $e_{sd} = 0$. In other words there is an implicit assumption that one has perfect alignment of the dq and xy axes. There is circularity in the calculation of e_{sd} – i.e. we are applying $u_{sd} = i_{sd}^* R_s$ relative to the control frame dq axes and then simply measuring the same applied voltage to the same axes. Errors in R_s will result in $e_{sd} \neq e_{sx}$, and therefore the flux loop will calculate

Fig. 9: Simulation of the current fed (i-i) NFO control algorithm.

an incorrect flux. Therefore if there are errors in R_s which cause misalignment this misalignment cannot be compensated for with the e_{sd} feedback signal as in the i-i case. From this point of view, the i-i control scheme would be a preferred option if R_s is not adjusted during the machine's operation. ♦

V. STATOR VERSUS ROTOR FLUX ORIENTATION NFO

The torque limitation of the stator flux vector control mentioned in Remark 2 can be overcome if the NFO aligns with the rotor flux vector. In this case the torque overload is limited only by the ability of the windings to conduct the large overload currents. Consider the stator voltage equations in a rotor flux oriented frame:

$$u_{sx} = R_s i_{sx} + \sigma L_s \frac{di_{sx}}{dt} + \frac{L_m^2}{L_r} \frac{d|i_{mr}|}{dt} - \sigma L_s \omega_{mr} i_{sy} \quad (8)$$

$$u_{sy} = R_s i_{sy} + \sigma L_s \frac{di_{sy}}{dt} + \sigma L_s \omega_{mr} i_{sx} + \omega_{mr} \frac{L_m^2}{L_r} |i_{mr}| \quad (9)$$

These equations are much more complex than (2) and (3). From equation (9) and with the NFO concept applied the angular

Fig. 10: Simulation of the v-i NFO control algorithm.

velocity of the rotor flux vector can be estimated as:

$$\omega_{mr} = \frac{u_{sy} - R_s i_{sy} - \sigma L_s \frac{di_{sy}}{dt}}{\frac{L_m}{L_r} |\psi_r^*| + \sigma L_s i_{sx}} \quad (10)$$

which implies a trickier integration to obtain the frame angular position than with the respective expression (6) for the stator flux orientation. From equation (8) it is clear that in steady state $e_{sx} = u_{sx} - R_s i_{sx} = -\sigma L_s \omega_{mr} i_{sy}$. This is a non-zero but still a relatively small value. So, similarly to the SFO version, non-zero e_{sx} values should mainly indicate frame misalignment. A block diagram of the rotor flux oriented NFO algorithm is shown in Figure 9b. This scheme was used in simulations and showed results close to that for the SFO control with the advantage of not being limited in maximum torque.

Remark 5: The rotor flux oriented NFO control retains the advantages of the stator flux oriented NFO control, such as low sensitivity to R_s value and indication of the frame misalignment

by a non-zero e_{sx} value. At the same time, it requires more parameters (σL_s) for its implementation. In some applications the latter could be an appropriate trade-off for overcoming the pull-out torque limit implied by the stator flux oriented control. ♦

Remark 6: Simulation results of the rotor flux oriented version of NFO are very similar to those obtained for stator flux oriented NFO. The rotor flux variant of the algorithm still has the same problem with static frame instability in regeneration as the stator flux variant.

VI. CONCLUSIONS

The main observations and conclusions from this paper are:

- NFO is a variant of SFO. NFO is much more robust with respect to errors in R_s as compared to SFO.
- Raw NFO has static reference frame instability in regeneration. This can be corrected by using e_{sd} in a feedback loop.
- The NFO variants for the current-fed, voltage-fed and voltage-current-fed induction machine are discussed and compared. The i-i version of NFO has the advantage that e_{sd} can be used as a feedback signal to correct frame instability and frame misalignment due to parameter errors. The v-v and v-i forms of NFO are very sensitive to R_s accuracy, and cannot use e_{sd} feedback.
- The stator flux version of NFO has a static torque limit. The rotor flux version overcomes this torque limit at the cost of more parameter dependence.

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