The Universal Field Oriented (UFO) Controller in the Airgap Reference Frame

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The Universal Field Oriented (UFO) controller operating in the airgap flux reference frame is applied to a current regulated PWM induction motor drive. Inside the induction motor, voltages induced in center tapped windings are used to sense directly the airgap flux position and amplitude. Field orientation is realized without any additional calculations requiring machine parameters. In steady state, the resulting Direct Universal Field Oriented (DUFO) controller is not affected by detuning errors and can operate during flux weakening up to the theoretical limits of the drive. The DUFO drive has an excellent dynamic performance even under strongly detuned conditions.

Furthermore, due to its high degree of generality the UFO controller is fully compatible with direct and indirect field orientation. As a consequence, it is feasible to switch over to Indirect Universal Field Orientation (IUFO) at low speed. The latter expands the use of the high performance induction motor drive down to standstill.

1. Introduction

Until present, enormous effort has been spent to improve direct and indirect field oriented controllers by design of complicated hardware and software in order to compensate for non ideal machine behaviour such as machine parameter variations due to temperature changes and non linearities caused by rotor deep bar effects⁽³⁾⁽⁴⁾ and magnetic saturation.

However, little attention has been given to the fundamental reason that causes the specific theoretical and practical problems related to all classical field oriented controllers. Indeed, classical field orientation accomplishes independent control of torque and flux with respect to the rotor flux of the induction machine. Acquiring information on the rotor flux vector is, in practise, very difficult and rather imprecise because the rotor flux is linked to the rotating member of the machine. From a theoretical viewpoint the rotor flux is "hidden" deeply in the machine equations and its calculation from

other flux or current vectors requires machine parameters (stray inductances or rotor time constants) which are difficult to measure. These facts often lead to a detuned operation of the drive.

Indirect Field Oriented (IFO) control is highly dependent on rotor parameters to predict the rotor flux position. Furthermore, it requires precise speed or shaft position encoders. Direct Field Oriented (DFO) control depends on machine stray inductances to calculate the rotor flux position because most existing methods do not sense the rotor flux directly. Most methods sense stator flux or airgap flux instead. In addition, unless Hall sensors are used, DFO controllers do not have the ability to control torque and flux at zero frequency. In many applications the usage of Hall sensors for airgap flux sensing is limited by constraints related to machine design and thermal conditions. Methods which sense rotor flux directly with rotor end ring current detectors are under investigation and appear to be promising to avoid the problems mentioned

above⁽¹⁶⁾. However, in many induction machines the construction of the induction machine itself (e.g. fans, cooling blades etc.) might prevent this method of flux detection to be successful.

In order to cope with the practical problems of direct flux sensing, Lipo et al.^{(6)~(9)} proposed a flux sensing technique which uses tapped stator windings for highly reliable airgap flux measurements. This flux sensor is suited for drives in which the minimum speed request is above 3 Hz. However, the control structure, like the all classical DFO controllers, requires the calculation of the rotor flux from the accurately measured airgap flux. The accuracy of this rotor flux calculator depends on the accuracy of the estimation of the rotor leakage inductance, which varies strongly in different operating modes. Because this calculator of rotor flux amplitude and position is integral part of the flux sensor, it is not possible to compensate for any detuning effects this might cause to the drive.

De Doncker⁽⁵⁾ proposed the Universal Field Oriented (UFO) controller which is capable of decoupling flux and torque in an arbitrary flux reference frame. With the UFO controller it is not required to decouple torque and flux with respect to the rotor flux reference frame. Other synchronous reference frames such as a reference frame linked to the stator flux or the airgap flux can be selected. Decoupled control of torque and flux in these reference frames has important practical benefits for DFO controllers which sense directly stator flux or airgap flux. Indeed, with the UFO decoupling equations it seems straightforward to control torque and flux of the induction machine within the reference frame of the flux sensor itself. The flux calculator is reduced to its basic Cartesian to polar coordinate transformation and is independent of machine parameters. This results in an exact flux sensor and can lead to a drive which has no detuning errors during steady state operation. This principle has already been demonstrated specifically in case of a stator flux oriented controller⁽¹³⁾.

Furthermore, it was proven that the basic topology of the decoupling network is identical for all synchronous reference vectors. Due to this high degree of generality the UFO controller is fully

compatible with all existing field oriented controllers, indirect as well as direct. As a consequence, the digital integration of the UFO scheme using a high speed digital signal processor (DSP) allows the drive designer to combine indirect and direct field orientation in the same drive. In fact, the total computation time is in the order 100 μ s using the Texas Instrument TMS 32010 DSP.

2. New proposed drive system

In this paper, the authors propose a new high performance drive using the UFO controller technique combined with the tapped stator winding induction motor. At low speeds (from zero to 3~5 Hz) the Indirect Universal Field Oriented (IUFO) is used. At speeds above 3~5 Hz the Direct Universal Field Oriented (DUFO) controller operating in the airgap flux reference frame is used. This controller measures the flux position using the tapped stator windings and is applicable over the whole speed range up to the flux weakening region.

One particular feature added to the drive is the ability to keep both controllers (IUFO and DUFO) alive and to combine them in a suitable manner in the different speed ranges such that a smooth transition is obtained from IUFO to DUFO.

3. Induction machine model in synchronous reference frame linked to the airgap flux vector

The induction machine equations expressed in the airgap reference frame (superscript h) using the qd components are:

3.1 Stator voltage equations

$$v_{qs}^h = r_s i_{qs}^h + \frac{d}{dt} \lambda_{qs}^h + \omega_h \lambda_{ds}^h \quad \dots\dots\dots (1)$$

$$v_{ds}^h = r_s i_{ds}^h + \frac{d}{dt} \lambda_{ds}^h - \omega_h \lambda_{qs}^h \quad \dots\dots\dots (2)$$

3.2 Rotor voltage equations

$$0 = r_r i_{qr}^h + \frac{d}{dt} \lambda_{qr}^h + (\omega_h - \omega_m) \lambda_{dr}^h \quad \dots\dots\dots (3)$$

$$0 = r_r i_{dr}^h + \frac{d}{dt} \lambda_{dr}^h - (\omega_h - \omega_m) \lambda_{qr}^h \quad \dots\dots\dots (4)$$

In this study the stator voltage equations are only useful for the analysis of the drive during flux

weakening. It is assumed that the current feedback loops of the CRPWM inverter cancel out completely the stator voltage dynamics.

The flux linkage equations give the relationship between the fluxes and the currents:

3.3 Flux linkage equations

$$\lambda_{qs}^h = (L_{ls} + L_h) i_{qs}^h + L_h i_{qr}^h = L_{ls} i_{qs}^h + \lambda_{qh}^h \quad (5)$$

$$\lambda_{ds}^h = (L_{ls} + L_h) i_{ds}^h + L_h i_{dr}^h = L_{ls} i_{ds}^h + \lambda_{dh}^h \quad (6)$$

$$\lambda_{qr}^h = (L_{lr} + L_h) i_{qr}^h + L_h i_{qs}^h = L_{lr} i_{qr}^h + \lambda_{qh}^h \quad (7)$$

$$\lambda_{dr}^h = (L_{lr} + L_h) i_{dr}^h + L_h i_{ds}^h = L_{lr} i_{dr}^h + \lambda_{dh}^h \quad (8)$$

The electromagnetic torque equations and the mechanical load equation of the induction motor drive complete the system equations:

$$T_e = \frac{3}{2} P (\lambda_{ds}^h i_{qs}^h - \lambda_{qs}^h i_{ds}^h) \\ = \frac{3}{2} P L_h (i_{qs}^h i_{dr}^h - i_{ds}^h i_{qr}^h) \quad (9)$$

$$\frac{J}{P} \frac{d\omega_m}{dt} = T_e - T_L \quad (10)$$

where:

- L_h : main inductance
- L_{ls} : stator leakage inductance
- L_{lr} : rotor leakage inductance
- $L_s = L_h + L_{ls}$: stator inductance
- $L_r = L_h + L_{lr}$: rotor inductance
- $\sigma = (L_r - L_h)/L_r$: coupling parameters
- P : number of pole pairs

The system variables are written according to the next convention:

x_{kj}

with :

- $k=q$; q axis (torque axis)
- $k=d$; d axis (flux axis)
- $j=r$; rotor quantities
- $j=s$; stator quantities
- $j=h$; airgap quantities
- $j=m$; mechanic rotor quantities (position)
- $i=h$; airgap flux reference frame
- $i=r$; rotor flux reference frame

In order to link the d -axis of the reference frame to a flux vector, one states that the q -component of this flux vector equals zero. In the case of the

airgap flux, one simply states that the q -component of the airgap flux equals zero:

$$\lambda_{qh}^h = 0 \quad (11)$$

This not only implies that the reference frame is fixed to the airgap flux but also that the airgap flux becomes a state variable of the transient machine model. Consequently, the field oriented controller derived from this model will be able to command directly the airgap flux.

In summary, the dynamic behaviour of the current fed motor is described by the Eqs (3) and (4). However, for a practical realization of the field oriented controller the rotor currents have to be eliminated because they are not directly accessible in the machine. Using the Eqs (7) and (8), it is possible to write:

$$\lambda_{dr}^h = (L_r/L_h) \lambda_{dh}^h - \sigma L_r i_{ds}^h \quad (12)$$

$$\lambda_{qr}^h = -\sigma L_r i_{qs}^h \quad (13)$$

$$i_{dr}^h = \frac{\lambda_{dh}^h}{L_h} - i_{ds}^h \quad (14)$$

$$i_{qr}^h = -i_{qs}^h \quad (15)$$

The derivation of the decoupling circuit can now proceed identically to all field oriented controllers developed so far. As a result, the rotor slip frequency (ω_s) and the d component of the stator current (i_{ds}^h) can be written⁽⁵⁾:

3.4 Decoupling circuit equations

$$\omega_s = \omega_h^m = \frac{i_{qs}^h + (L_{lr}/R_r)(di_{qs}^h/dt)}{(1/L_h)(L_r/R_r)\lambda_{dh}^h - (L_{lr}/R_r)i_{ds}^h} \quad (16)$$

$$\left(1 + \frac{L_{lr}}{R_r} \frac{d}{dt}\right) i_{ds}^h = \frac{1}{L_h} \left(1 + \frac{L_r}{R_r} \frac{d}{dt}\right) \lambda_{dh}^h \\ + \omega_h^m \frac{L_{lr}}{R_r} i_{qs}^h \quad (17)$$

and the torque equation becomes:

$$T_e = 3/2 P i_{qs}^h \lambda_{dh}^h \quad (18)$$

4. The airgap flux field oriented controller

Eq. (17) shows that a coupling exists between the stator current torque component and the air gap flux. As a consequence, in order to prevent a transient in the airgap flux, any change of torque command requires a change of the stator current d component. This approach is different from the classical rotor flux field orientation where the stator current d component is directly proportional to the

Then, the Direct Universal Field Oriented (DUFO) controller in the airgap flux reference frame, will be analyzed, showing that the parameter deviation sensitivity is greatly eliminated.

In particular, we will make next assumptions:

- the current regulated PWM inverter is an ideal current source;
- since the airgap flux is directly measured, the airgap flux is exactly known both in amplitude and angular position.

For the DRFO, the slip frequency, in steady state conditions, can be expressed by the following equation:

$$\left(\omega_{r0}^m\right)^2 - \frac{L_h^2 \hat{L}_h \lambda_{dr}^*}{\Delta L_\sigma L_r \tau_r I_{qso}} \omega_{r0}^m + \left[\frac{L_h^2 - \Delta L_\sigma L_r}{\Delta L_\sigma L_r \tau_r} \right]^2 = 0 \quad \dots\dots\dots (23)$$

In Eq. (23) the rotor time constant τ_r equals:

$$\tau_r = L_r / R_r$$

The error on the transient inductance ΔL_σ , which is approximately equal to the rotor leakage inductance, is given by:

$$\Delta L_\sigma = \frac{\hat{L}_h}{L_r} \hat{L}_{lr} - \frac{L_h}{L_r} L_{lr}$$

Eq. (23) has real solutions only if:

$$T_e^* \leq \frac{3P}{8} \left| \frac{\hat{L}_h^2 L_h^2 \lambda_{dr}^{*2}}{\Delta L_\sigma \hat{L}_r (L_h^2 - \Delta L_\sigma \hat{L}_r)} \right| \dots\dots\dots (24)$$

Eq. (24) defines the range of allowable torque commands. Notice that the pull out torque of the DRFO drive varies with the error on the transient leakage inductance which is a function of the unknown machine parameters and the estimated controller parameters. For the induction machine used in this study, the calculated pull out torque is 177 Nm when the rotor leakage inductance of the DRFO controller is detuned by an additional 110%.

For the DUFO case, solving the equations of the direct airgap flux oriented system, one can obtain the following steady state equation:

$$\left(\omega_{ho}^m\right)^2 - \frac{(1-\sigma)\lambda_{dh}^*}{\sigma^2 L_h \tau_r I_{qso}} \omega_{ho}^m - \left(\frac{1}{\sigma \tau_r}\right)^2 = 0 \quad \dots (25)$$

Eq. (25) yields the condition for static stability:

$$T_e^* \leq \frac{3P}{8} \frac{(1-\sigma)}{\sigma L_h} \lambda_{dh}^{*2} \quad \dots\dots\dots (26)$$

Eq. (26) defines the range of allowable torque commands for the DUFO controller. The pull out

torque does not vary with errors in the estimated leakage inductance and is equal to the natural motor pull out torque. As a result, the stability limit of the DUFO controller is more predictable.

With reference to the motor used for our experiments (see Appendix), the pull out torque is 205 Nm with the DUFO controller i.e. the motor natural pull out torque. As a consequence, in detuned conditions with the rotor leakage inductance increased by 110%, the reduction in pull out torque using the DRFO is about 15%. One can conclude that the DUFO controller offers a better utilization of the drive in all operating conditions.

This result can be understood from the fact that the DRFO system needs the leakage inductance in its flux feedback path. On the other hand, the new DUFO controller has the sensitive parameters in the decoupler which is in the forward path. Thus, the detuning effects can be corrected by the feedback control of the flux loop, yielding a robust controller.

6. Field orientation in the airgap flux reference frame using tapped stator windings

The practical realization of the flux sensor, which was proposed in the previous paragraph, can be obtained by sensing the airgap with a tapped stator winding induction motor. In fact, this method for measuring flux utilizes voltages induced in two coils of the three phase motor⁽⁶⁾. The voltages are accessed by making connection points available within the motor stator windings. Since two coils in the same phase have the same currents and since they are wound similarly, they have the same resistance. By taking the voltage difference between two such coils, the IR drop can be cancelled leaving only the difference between the airgap flux derivatives. The dq components of the airgap flux can be derived using the next equations:

$$\lambda_{dh}^s = k_1 \left[\int (v_{a1} - v_{a2}) dt \right] \dots\dots\dots (27)$$

$$\lambda_{qh}^s = k_2 \left[2 \int (v_{b1} - v_{b2}) dt + \int (v_{a1} - v_{a2}) dt \right] \dots\dots\dots (28)$$

where λ_{dh}^s is the d -component of the air gap flux in

the stationary reference frame, λ_{qh}^s is the q -component of the air gap flux in the stationary reference frame. Subscripts a_1 and a_2 indicate the coils related to phase a and subscripts b_1 and b_2 the coils related to phase b .

Once the airgap flux is sensed, it is necessary to decouple flux and torque in the airgap flux reference frame in order to avoid machine parameters in the flux position calculator. The UFO controller with airgap flux control will not depend on the rotor leakage inductance which is unavoidable when the rotor flux is chosen as a reference vector (which is the classical approach in field orientation). As a result, the airgap flux direct universal controller (DUFO) cannot suffer from detuning errors and steady state stability problems. The resulting drive is robust up to very high speeds.

However, at zero frequency no information of flux position can be obtained and hence no torque control is possible. In the next paragraph, a simple strategy which overcomes this problem is presented.

7. Combined indirect and direct field oriented control in the airgap flux reference frame

In Fig. 1 the Indirect Universal Field Oriented (IUFO) controller is shown and the Direct Universal Field Oriented (DUFO) controller is depicted in Fig. 2.

The two structures are so similar that it is possible to change dynamically from one controller to the other without any change of the controller hardware. A drive which has to operate over a wide speed range can combine these different UFO control strategies. At high speeds the DUFO controller which uses the airgap flux reference frame is selected. As explained in the previous sections, no steady state detuning can occur which are caused by machine parameter variations or controller estimation errors. At low speeds the IUFO controller is used.

However, the transition between the two schemes is not so easy, especially when the IUFO controller is strongly detuned. Small differences in the variables can cause large transients. A solution to this problem is proposed next.

(a) Output and command torque

(b) Rotor flux

(c) d -axis stator current component

Fig. 3. Response of a detuned Direct Rotor Flux Field oriented (DRFO) system.

Since the direct and indirect structure in the universal scheme are similar, a major part of the algorithm is common. One can easily keep both controllers working in parallel. The calculated variables of the two controllers are then combined with a suitable weighting factor. This weighting factor should be related to the ratio of actual speed

Fig. 4. Response of a detuned Direct Universal Field Oriented (DUFO) system.

and a selected speed threshold of commutation between IUFO and DUFO.

The applied formula to a generic variable G (flux, displacement, decoupling current i_{dqh}) is shown below:

$$G = w G_{DUFO} + (1 - w) G_{IUFO} \quad (29)$$

with:

G_{DUFO} : DUFO controller output variable,

G_{IUFO} : IUFO controller output variable,

w : weighting factor, defined as:

$$w = \left(\frac{|\omega|}{\omega_{th}} \right)^n \quad \text{if } |\omega| < \omega_{th} \quad (30)$$

$$w = 1 \quad \text{if } |\omega| > \omega_{th} \quad (31)$$

where:

ω : actual electrical speed,

ω_{th} : speed threshold for IUFO or DUFO,

n : weighting factor exponent.

At low speeds and frequencies the signal to noise ratio of the DUFO flux sensor is too low for a reliable measurement. Hence, the direct field

oriented controller has to be suppressed in order to minimize errors. On the other hand, around the speed threshold level a fast transition from indirect to direct field orientation is necessary. In order to match these constraints the weighting factor must have a low derivative at low speeds and a high derivative at the threshold speed. By simulating the transitions between IUFO and DUFO, a weighting factor exponent of 2 was selected. This choice also allows a simple practical implementation in a signal processor which has a fast multiplier.

8. Simulation results

Digital simulations were carried out to study the performance of the overall system. In the simulations we examined the following:

- (1) properly tuned DRFO and DUFO in transient and steady state conditions,
- (2) detuned DRFO and DUFO in transient and steady state conditions,

Fig. 5. Transition between IUFO and DUFO system.

(3) IUFO to DUFO transitions.

In order to verify the stability limits, the CRPWM inverter is able to supply much more than the rated motor current. In this way, the machine can be loaded with a load torque T_L almost three times the rated torque and the pull out torque limit can be reached.

8.1 Properly tuned DRFO and DUFO

Both controllers gave an excellent response to instantaneous torque commands. The load torque (T_L) was 200 Nm, while the motor pull out torque at rated voltage is 205 Nm. Despite the high load torque, any change in the torque command does not affect the flux. The decoupling between the two axes is attained and the torque and the flux follow the commands.

8.2 Detuned DRFO and DUFO

The performance of a detuned DRFO system is shown in Fig. 3. In this simulation, the estimated rotor leakage inductance is set to 7 mH, whereas the

nominal value is 3.3 mH. The load torque T_L is 200 Nm and is larger than the detuning pull out torque which equals 177 Nm. The rotor flux position and amplitude is not properly estimated and any changes in the torque affects the rotor flux. The decoupling between the two axis is not attained and the system becomes unstable. The stator current d component (I_{dSE}) will continue to drop until the current regulators saturate (not shown in Fig. 3.).

The same detuning conditions are simulated for the DUFO. The results are shown in Fig. 4. Since the estimated leakage inductance is 110% larger than the nominal one, the decoupling circuit overcompensates the changes of I_{qs}^h . However, the flux feedback loop will force the stator current d component to a value such that the airgap flux is constant.

8.3 Transition between IUFO and DUFO

As already mentioned above, the transition between the indirect and direct system must be programmed in order to avoid heavy transients

inside the machine. As it was explained above, the weighting factor must have a low derivative at low speeds and high derivative around the threshold speed. Fig. 5 shows complete transitions between 0 to 800 rpm and between 800 to -250 rpm, with the threshold speed set at 200 rpm and the weighting factor exponent equal to 2.

9. Conclusions

The flux sensing technique of the center tapped stator windings combined with the UFO controller operating in the airgap flux reference frame leads to a robust high performance drive with no dependency on machine parameters in steady state. As a result, the drive shows no detuning errors. The steady state stability limits, which are important in the flux weakening region, are as high as one can theoretically obtain. The proposed method for the transition between indirect universal field orientation and direct universal field orientation is an attractive solution to overcome the noise problems of the direct field orientation at very low frequencies.

One can also conclude that the UFO algorithm has no additional hardware costs compared to other field orientation schemes which use a DSP. The overall solution becomes an optimal match between the components of the drive and the controller which is not overloaded with heavy calculations such as parameter adaptation or estimation. Finally, the additional position or speed sensor for the IFO controller is very often necessary for other purposes such as the outer speed and position feedback loops. Consequently, for these cases the new drive design is actually at no extra cost.

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Appendix

Data of the stator tapped winding prototype induction motor

A three phase stator tapped induction motor has been designed and built. The new motor is a standard motor with taps on the stator winding and extra signal terminals in order to detect directly the airgap flux⁽⁶⁾. The motor has 36 stator slots and 28 rotor slots.

Rated Output Power	11 kW
Rated Voltage	380 V

Rated Current	21.6 A
No-load Current	8 A
Maximum Torque	205 Nm
Rated Torque	70 Nm
Number of Pole Pairs	2
Rated Speed	1,430 rpm
Maximum Speed	3,000 rpm
Stator Resistance	0.371 Ω
Rotor Resistance	0.415 Ω
Stator Leakage Inductance	2.72 mH
Rotor Leakage Inductance	3.3 mH
Main Inductance	84.22 mH

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