Synchronization Angle determination in DVCSFO of DFIM naval propulsion

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Keywords

«Variable speed drive», «Induction Motor», «Flux Model», «Reliability», «Power Sharing»

Abstract

This paper presents the **D**ual **V**ector **C**ontrol with **S**tator **F**lux **O**rientation (**DVCSFO**) of Doubly Fed Induction Machine (DFIM). This DFIM operates in motor mode and is intended for naval propulsion. This machine, without permanent magnets, is fed by two identical PWM VSIs. It has been specially designed to share its power equally between the stator and the rotor. The previous studies have discussed the cooling of all system carried out by the water, for the stator and rotating rotor of DFIM and also for two IGBT VSIs. The stator and rotor fluxes are controlled in rotating «d,q» reference frame and must be maintained at their nominal value. Therefore, the DVCSFO strategy requires precise knowledge of all transformation angles and especially the Synchronization Angle when an incremental encoder is used as a speed sensor. Unlike the squirrel cage asynchronous machine, this DFIM actuator can be blocked if the synchronization angle is neglected in Park transformations.

Introduction

In modern naval propulsion concepts, the electrical machines have a crucial role, moving towards "the more electric" or even "all electric" ship and must respect the environmental demand "Clean-Sea" and "Clean-Ship". The authors propose the DFIM for naval propulsion application, where this machine works in motor mode and offers some advantages as listed below:

- high degree of freedom,
- excellent operation at very low speed and even when stopped,
- natural structural redundancy in case of VSI failure,
- active power dispatching between stator P_s and rotor P_r sides (Fig.1),
- total losses of two PWM VSIs are lower than the same power squirrel cage induction machine supplied by only one PWM VSI,
- wide rotation speed range with nominal torque.

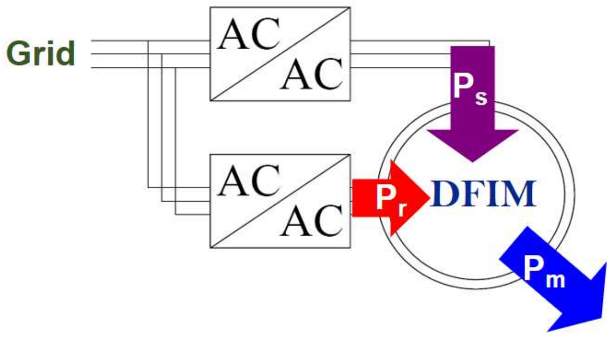

Fig. 1: Active power dispatching between the stator and rotor armatures of DIFIM

In this paper the authors discuss an important problem of Real Time control realization of a Multi-Pole DFIM propulsion. The multipolar solution is applied to reduce the volume and the weight of the motor, operates in an embedded system.
The DVCSFO strategy was chosen to guarantee an optimal DFIM drive system operation according to a real naval propulsion specification.
As the system operating and performances depend on position of the stator and rotor fluxes, therefore to reach the control performances and its expectations, the synchronization angle must be cancelled before any start up. This angle is often ignored in FOC of classical squirrel cage induction machine. The synchronization angle precise information is required in the first step of DVCSFO strategy and the main key of DFIM starting and achieving performances.

DIFIM propulsion presentation

The studied DFIM naval propulsion structure, shown in the Fig. 2, is composed of:

- AC grid,
- two AC/AC converters (two rectifiers and two PWM VSIs),
- DFIM propulsion,
- symmetrical three blade propeller load,
- transformer between the AC grid and the rectifier to respect the voltage level on the rotor and stator sides.

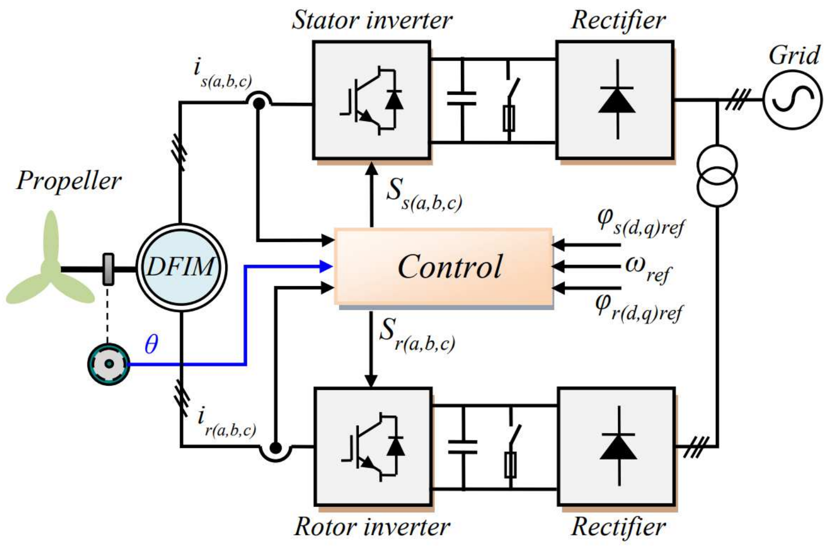

Fig. 2: General diagram of DFIM naval propulsion

DFIM actuator modelling

We have chosen for this study the flux model of the DFIM [3] defined in rotating d,q reference frame given in the Fig. 3 and described by equations of electrical part of the machine (1) and (2), with the stator flux orientation such as $\Phi_{sd}=\Phi_s$ and $\Phi_{sq}=0$.

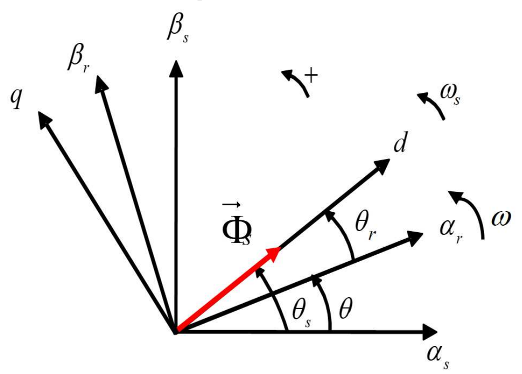

Fig. 2: Vector diagram chosen for DFIM modelling

The electrical equations for the stator (1) and rotor (2) of DIFIM can be written as follows:

$$V_{sd} = \frac{R_s}{\sigma L_s}\Phi_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s \Phi_{sq} - \frac{R_s M_{sr}}{\sigma L_r L_s}\Phi_{rd}$$
$$V_{sq} = \frac{R_s}{\sigma L_s}\Phi_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s \Phi_{sd} - \frac{R_s M_{sr}}{\sigma L_r L_s}\Phi_{rq} \qquad (1)$$

$$V_{rd} = \frac{R_r}{\sigma L_r}\Phi_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r \Phi_{rq} - \frac{R_r M_{sr}}{\sigma L_r L_s}\Phi_{sd}$$
$$V_{rq} = \frac{R_r}{\sigma L_r}\Phi_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r \Phi_{rd} - \frac{R_r M_{sr}}{\sigma L_r L_s}\Phi_{sq} \qquad (2)$$

When the motor is non saturated, the linear relation can be expressed between the fluxes and currents as below (3):

$$\begin{cases} \Phi_{sd} = L_s I_{sd} + M_{sr} I_{rd} \\ \Phi_{sq} = L_s I_{sq} + M_{sr} I_{rq} \\ \Phi_{rd} = L_r I_{rd} + M_{sr} I_{sd} \\ \Phi_{rq} = L_r I_{rq} + M_{sr} I_{sq} \end{cases} \qquad (3)$$

Finally, the mechanical equation is expressed by (4)

$$J_t \frac{d\Omega}{dt} = T_{em} - f_t \Omega - T_L$$
$$T_{em} = \frac{N_p M_{sr}}{L_s L_r \sigma}(\Phi_{sq}\Phi_{rd} - \Phi_{sd}\Phi_{rq}) \qquad (4)$$

where $V_{sd}, V_{sq}, V_{rd}, V_{rq}$ - direct and quadrature stator and rotor voltages

$I_{sd}, I_{sq}, I_{rd}, I_{rq}$ - direct and q quadrature stator and rotor currents

$\Phi_{sd}, \Phi_{sq}, \Phi_{rd}, \Phi_{rq}$ - direct and quadrature stator and rotor fluxes

R_s, R_r - stator and rotor phase resistances,

L_s, L_r - stator and rotor cyclic inductances

M_{sr} - mutual cyclic stator/rotor inductance

$\sigma=1-M_{sr}^2/L_s/L_r$ - dispersion ratio,

ω_r, ω_s - rotor and stator velocities.

θ_s - stator angle between α_s axis of the stationary reference frame and d axis,

θ_r - angle between the α_r axis of the rotor reference frame and d axis

θ - electrical angle between the stator and the rotor

J_t - DFIM and load total inertia

f_t - total viscous friction coefficient

N_p - number of pairs of poles

T_{em} - electromagnetic torque

T_L	- load torque
Ω	- mechanical rotation speed (rad/s)
$\omega = N_p\ \Omega$	- electrical rotation speed (rad/s)

We can dress the general diagram of DIFIM actuator (Fig. 4) using the transfer functions of its electrical modes expressed as follows:

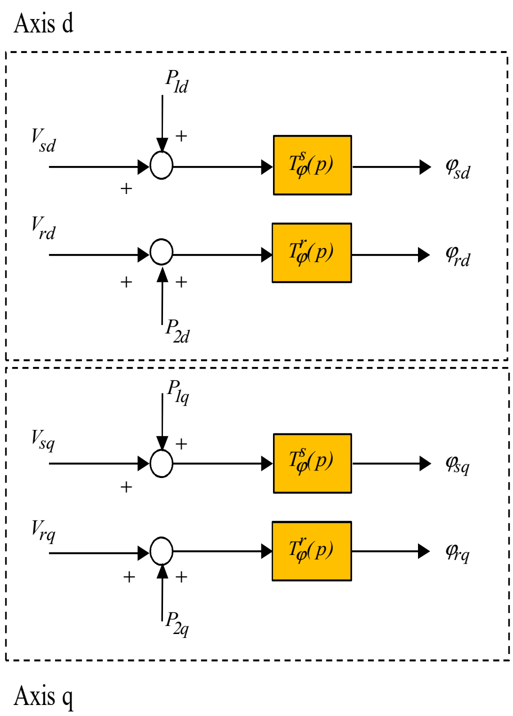

Fig. 3: DFIM diagram of its electrical modes

For index i=d, q

$$T_\varphi^s(p) = \frac{V_{siref} + P_{1i}}{\Phi_{si}} \qquad T_\varphi^s(p) = \frac{\dfrac{L_s\sigma}{R_s}}{p\dfrac{L_s\sigma}{R_s} + 1}$$

$$T_\varphi^r(p) = \frac{V_{riref} + P_{2i}}{\Phi_{ri}} \qquad T_\varphi^r(p) = \frac{\dfrac{L_r\sigma}{R_r}}{p\dfrac{L_s\sigma}{R_r} + 1} \qquad (5)$$

The coupling terms are expressed as below:

$$\underline{P} = \begin{pmatrix} P_{1d} \\ P_{1q} \\ P_{2d} \\ P_{2q} \end{pmatrix} = \begin{pmatrix} \dfrac{R_s M_{sr}}{L_r L_s \sigma}\Phi_{rd} + \omega_s \Phi_{sq} \\ \dfrac{R_s M_{sr}}{L_r L_s \sigma}\Phi_{rq} - \omega_s \Phi_{sd} \\ \dfrac{R_s M_{sr}}{L_r L_s \sigma}\Phi_{sd} + \omega_s \Phi_{rq} \\ \dfrac{R_s M_{sr}}{L_r L_s \sigma}\Phi_{sq} - \omega_s \Phi_{rd} \end{pmatrix} \qquad (6)$$

We add also the diagram of mechanical mode shown in the fig. 5, where T_L corresponds to load torque created by propeller, T_{em} is electromagnetic torque issue from DFIM and defined by equation (4) given previously. The direct and quadrature stator and rotor fluxes are expressed in (3). For non-saturated DFIM we obtain the linear relations between the stator and rotor fluxes and currents.
The mechanical equation can by written by (4), with:

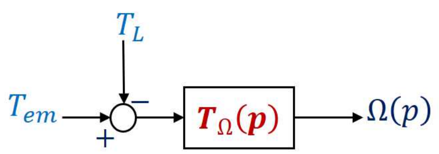

Fig. 4: DFIM diagram of its mechanical mode

The transfer function of mechanical mode of this DFIM actuator, can be formulated by:

$$T_\Omega(p) = \frac{\frac{1}{f_t}}{1 + \frac{J_t}{f_t}p} \qquad (7)$$

DVCSFO strategy of DFIM propulsion drive

Now we present the control diagram for the DFIM propulsion which is defined from the inverse model of the system. So, the general scheme of this control is given in the Fig. 6. We observe that first, the fluxes Φs and Φr have to be installed. This magnetization step must be preceded by the alignment of the two fluxes, stator and rotor. In this phase the synchronization angle will be determined precisely. This method is made automatically and will be presented in the next part of this paper.

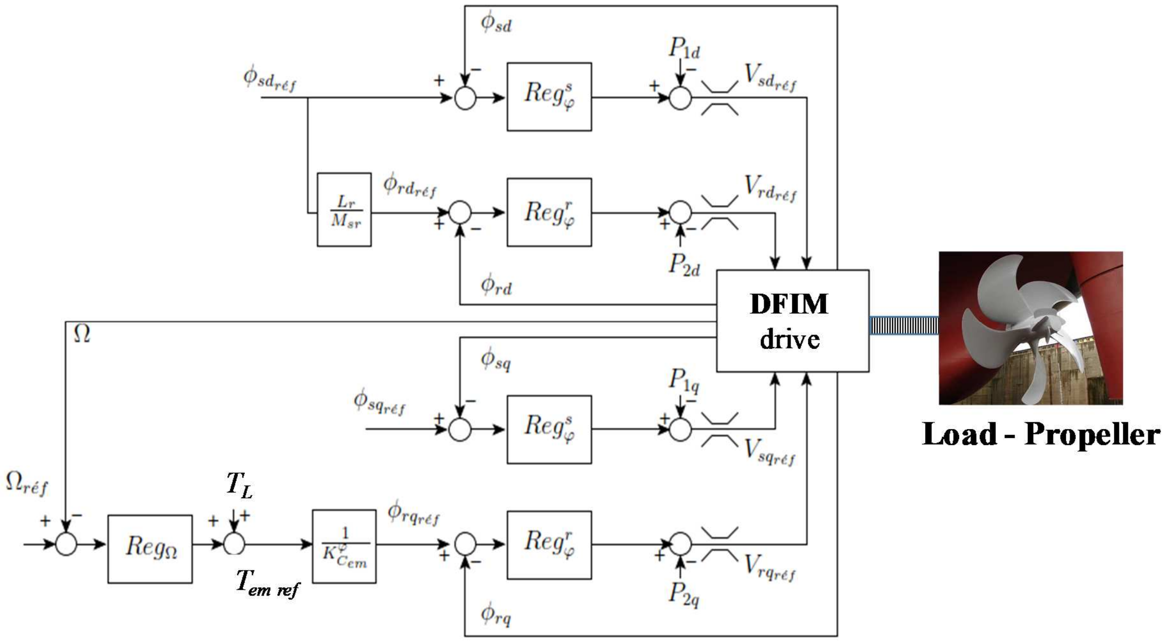

Fig. 5: General diagram for DVCSFO strategy of DIFIM propulsion

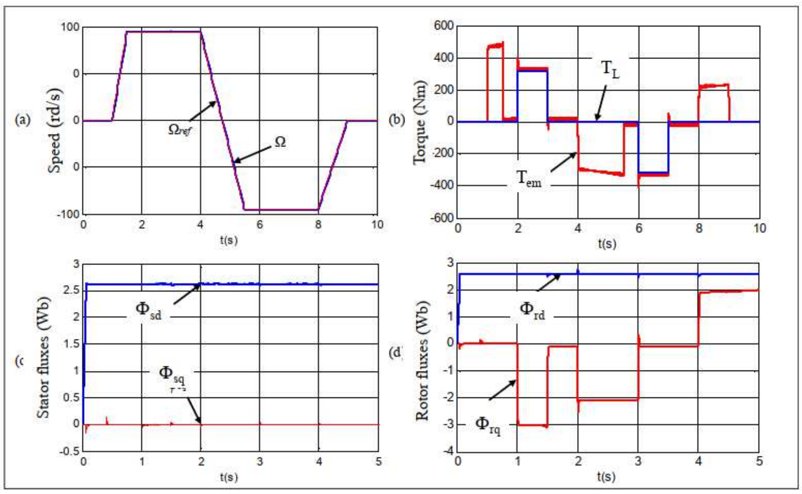

Fig. 6: 30kW DIFIM propulsion behavior during the operation test in four quadrants torque-speed plane

So, after the magnetization phase with installation of the two stator and rotor fluxes, the DFIM is started and stabilizes its rotation speed according to the imposed reference value. A reversal of the rotation direction is then ensured. The constant speed is also guaranteed in the opposite direction. Then, the DFIM returns to zero speed according to the imposed reference value.
It must be noted that this satisfactory DIFIM working will be problematic in real ship condition. In all laboratory tests, the Park transformations can be made with perfect angles. As it was write previously, the starting condition of this machine requires the perfect alignment of two stator and rotor fluxes. When this condition is not respected the DFIM starting is impossible.

The authors propose the generic and reliable method to guarantee the good DFIM starting in real operating conditions and especially delicate for the multi-pole, high voltage and high power DFIM propulsion.

Synchronization angle determination for reliable DFIM propulsion

The procedure for determining the synchronization angle of a DFIM having multi-poles must be carried out before its starting. As this machine can have several rotor shaft positions and therefore the different initial rotor angle defined as Θ_r.

We recall that in the vector control carried out in the d,q reference frame the Park transformation are very important and depends on the stator and rotor flux positions Θ_s and Θ_r as shown in Fig. 3. According to the control strategy conditions, these positions can be defined from the frequency or angular self-piloting laws. Due to the realization adapted to our digital control architecture we prefer to apply the angular self-piloting illustrated in Fig. 8

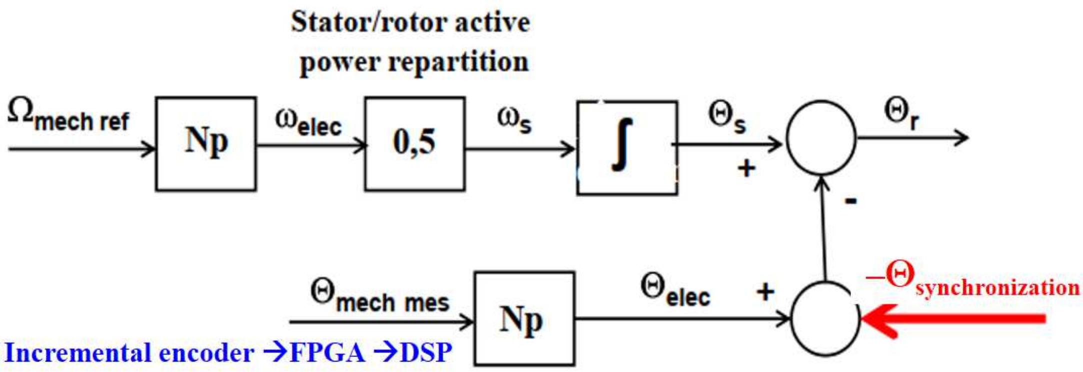

Fig. 7: Principle of angular self-piloting with correction term of synchronization angle

It can be noted that according to the DVCSFO strategy, the stator flux orientation with "d" axis requires the precise definition of its position Θ_s. So, from the reference value of mechanical rotation speed $\Omega_{mecaref}$ expressed in rad/s, we calculate the reference of electrical rotation speed ω_{elec} Next, using the active stator and rotor power repartition ratio equal to 0,5 we obtain the stator velocity ω_s. Its integration gives the stator flux position Θ_s. In squirrel cage induction machine the rotor flux position Θ_r is obtained by simple subtracting the electric position Θ_{elec} from Θ_s.

When the initial conditions for all angles are equal to zero, the synchronization angle is also equal to zero and the control algorithm DVCSFO is realized correctly. In the DFIM real operating conditions and for multi-poles DFIM, the synchronization angle has to be known precisely to introduce it as correction term for Θ_r calculation. Finally, we use the modified angular self-piloting shown in the Fig. 8. One observe that rotor flux position Θ_r is not obtained by direct subtracting the measured electrical position $\Theta_{elec\ mes}$ from stator flux position Θ_s, but this initially known synchronization angle, has to be introduced as correcting term $\Theta_{synchronization}$ (red indication in the Fig.8).

In fine, for 3-phase, 6 poles 30kW DFIM to determine this initial electric rotor position we have to consider its rotor structure. The synchronization angle of fluxes will be find by pre-supplying the first stator phase with DC voltage V_{s1}=+V, two other stator phases are fed also with DC voltages $V_{s2}=V_{s3}$=-V/2. The rotor will be supplied in the same way with DC voltages but theirs signs will be opposite, i.e. V_{r1}=-V and $V_{r2}=V_s$= +V/2. For 3 pairs of DFIM poles the initial rotor position can be different and situated in one of three sectors (red indication). Each sector of 2π/3 rad (120°) corresponds to one pair of poles (Fig. 9)

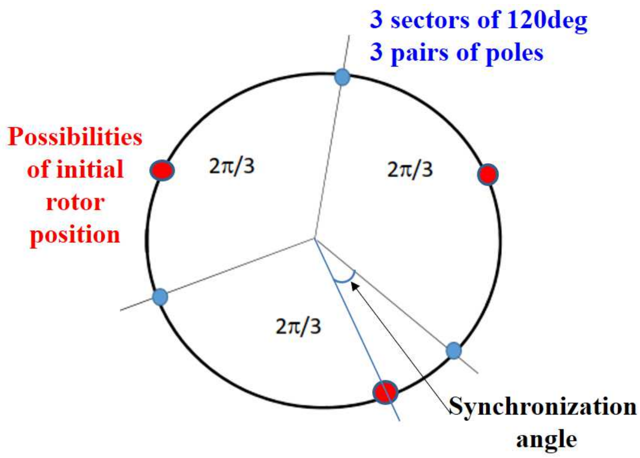

Fig. 8: Synchronization angle can be find inside of 120° sector corresponding to each pair of poles

First, we have to verify if the machine is fed to operate in motor mode. So, if the sequences of the 3 phases of the stator and the rotor are correct, then the DFIM has to be placed in a squirrel cage induction machine topology successively on the stator side or on the rotor side. For these topologies the DFIM must rotate in the opposite direction. It can be noted that this verification is made applying real time system and software reconfigurations, i.e. programmable short circuits in the stator or in the rotor to obtain the squirrel cage induction motor operation.

The synchronization angle measurement is made by fixing the rotor in any position, next we send 3 DC modulating signals Vs1, Vs2 and Vs3 to stator PWM modulator as it was described previously. We apply also to rotor PWM modulator 3 modulating signals. These DC supply provoke that the rotor and stator fluxes are aligned. The modulators are realized with FPGA solution operating with fixed point format, whereas the modulating signals are sent from DSP working with floating point format. So, the special registers allow to adapt these formats of the data issued: from DSP sent to FPGA and from FPGA sent to DSP.

So, to define the synchronization angle, first we must determine the number of sector where the rotor was stopped, next the angle value inside this sector has to be defined. If an angle of $2\pi rad$ (or of 360 degrees) is coded by 2048, each sector is characterized by g=2048/3 (or 120degrees per sector).

Consequently, after a reading of FPGA data, “N” which can be a value found between 0 and 2048, is transferred to DSP. This value must be divided by “g” to obtain the final result containing the sector number X,00 and 0,xx corresponds to angle inside this sector. To find this angle expressed in degrees we calculate 0,xx*120°. To determine Θ_r this angle must be expressed in doubly precision format compatible to DSP algorithm and is the synchronization angle to introduce it as correction term in modified angular self-piloting.

In any case, there is always a non-zero angle which should be compensated in the control strategy, it due to the fact of the mechanical shaft elasticity, torsion impact and the accuracy of the speed sensor.

DVCSFO strategy – task management

This DVCSFO strategy is implemented on a digital system containing a DSP card, TMS320C6713 from TEXAS INSTRUMENT, associated with the EP1K 100QC 208-2 FPGA card from ALTERA and an ADC/DAC interfaces card (THS10064 / TLC7628CDW) used to receive the current and voltage measurements. The Fig. 10 shows the principal task management of this control strategy where all algorithmic part is coded in DSP and interruptions, data acquisition, dead time and also modulation are programmed in FPGA.

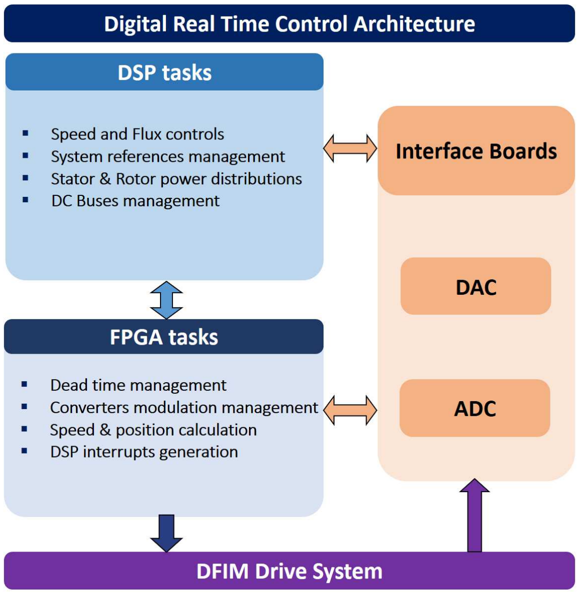

Fig. 9: Task management of DVCSFO strategy for DFIM propulsion

Conclusion

In this paper the authors present very important aspect concerning the synchronization angle which influences the quality of DVCSFO strategy applied to DFIM naval propulsion. This solution is interesting because the applied machine is Special design DFIM drive was designed to accept the active power distribution equivalently between stator and rotor. Consequently, the stator and rotor PWM VSIs have the same structure and the same sizing. Multi-poles, high voltage and high power DFIM drive allowing the best solution for this embedded system with weight and volume reduction. This introduces some difficulties in the control of the machine.

To guarantee the high reliability in all operating point the quality of proposed strategy has to be required. So, all phases of this control must be sure, i.e. starting, magnetization and four quadrants of torque/speed plane operation according to the specific naval conditions the synchronization angle is known precisely. We focused this presentation on the “synchronization angle” determination conditioning all transformations of control variables, necessary to good working of proposed DVCSFO. We affirm that the starting of this DFIM propulsion is possible when the synchronization angle is known precisely. This angle determination is not simple when the DFIM drive has many poles and when we work using the incremental speed sensor placed on the load side of this drive system.

To solve the synchronization angle problem, we recommend to use an absolute encoder instead of an incremental encoder or a sensorless control strategy.

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