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FPGA-based implementation of sensorless AC drive controllers for embedded Electrical Systems

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--ABSTRACT---
The aim of this paper is to present FPGA (Field Programmable Gate Array) based implementation of sensorless AC drive controllers for embedded electrical systems. For very low speed and standstill, the injection of a rotating high frequency voltage in the vector control scheme. Implemenatation of sensorless controllers strcture using FPGA.

INDEX TERMS: *Field Programmable Gate Array, Extended Kalman Filter, rotating high frequency signal injection,*

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I. INTRODUCTION

Nowadays, the embedded electrical systems are playing an increasingly important role in industrial control applications in different domains such as automotive, space and aircraft domains. The rising industrial demands in terms of performance and reliability require the use of complex and efficient control algorithms associated with high performance digital technologies. This is typically the case of aircraft embedded applications in the context of More Electrical Aircraft (EMA) industrial objectives. Along this trend and when focusing on AC drive applications, the sensorless controllers are becoming an interesting alternative to standard controllers. Therefore, many scientific and industrial researches have been focused on thanks to their attractive cost and size reduction associated to high reliability. Depending on the speed range, many estimation methods of rotor position were investigated. At standstill, the method based on injecting rotating or pulsating high has proved good performance. For medium and high speed range, the Extended Kalman Filter (EKF) appears to be an efficient candidate for the online estimation of speed and rotor position. Such sensorless controllers are well known for their complex computation which represents a real design challenge for implementing these strategies for embedded systems. Consequently, the use of efficient digital technologies became primordial since they allow the implementation of such complex controllers .implementation of such complex controllers.Among these technologies, the Field Programmable Gate Arrays (FPGAs) present a great interest to implement such complex algorithms. Indeed, FPGAs provide high integration density and modularity. They also offer the possibility to design very powerful dedicated parallel architectures which can dramatically reduce the execution time. For a challenging aircraft embedded system, the development of FPGA-based Intellectual Property (IP) modules is well convenient. It provides portability of modules between different targets. Consequently, it avoids losing time in development and certification which decreases the whole cost development system. Besides, for these critical applications, where the safety is of prime importance, the configuration must be kept against the SEU (Single Event Upset) radiations and even when power is off. In this sense, FPGA Flash RAM technology has also demonstrated its efficiency in term of reliability.

The final objective is to implement the two estimation methods in the same FPGA target. Firstly, the HF injection method is tested with 40 kVA BSSG using a FPGA Actel A3P1000 type. Secondly, the EKF is performed with Standard Synchronous Actuator (SSA) using FPGA Xilinx Virtex-2P.*Position of Sensors:-* The present rotor position detection in many PMSM machines is carried out with a resolver, which connected to the rotor shaft gives the rotor angle needed in the field oriented vector control. A resolver can be described as a combination of a small electrical motor, built up with a rotor and stator, and a rotating transformer since the voltages are induced between different windings. The stator usually contains three windings while the rotor holds one.

A high frequency reference voltage is applied to one of the stator windings, the primary side of the rotating transformer, exciting a current in the secondary side or the rotor winding. This way, no brushes or slip rings are needed in the resolver. Since this voltage is not used to produce any torque, the amplitude can be kept low, around 5 V, with a frequency at about 5 kHz. The two remaining windings in the stator are placed opposite to the first one, with a mutual distance of 90 degrees. The voltages in the two phase windings will be the injected reference voltage multiplied with sinus and cosines of the angle respectively. This makes the absolute angle, determinable with arctan (u. sinθR/ cosθR) and hence, the rotor detection will not be affected by changes in injected voltage that may occur due to temperature changes or ageing. [5] The basic resolver is built as a two pole machine which means that the mechanical and the electrical degrees agree with each other, but with multiple poles, the achieved accuracy can be better. The drawback is that the mechanical and the electrical degree will no longer agree.

Sensorless control:- High quality information about the rotor flux angle is crucial in field oriented control systems. The most common way to attain this information has been to add a dedicated sensor to the rotor shaft. This has a few disadvantages especially in drive systems used in automotive applications. Its physical size is a large drawback when designing the motor. The length of the machine is often critical due to constraints in the power train. This makes it sometimes impossible to fit a standard mechanical sensor. [9]The sensors can also cause problems in terms of reliability as they are sensitive to shock and vibration, optical sensors like encoders are in addition sensitive to dirt. A sensor connected through long cables can also be sensitive to disturbances.[8] A sensor fulfilling all requirements is often expensive, why removing it would constitute an important cost reduction. A control system that not has to rely on a mechanical position sensor would therefore be favorable, a so called sensorless control system. [9] To solve this problem, signal-injection methods have been developed taking advantage of that the rotor is salient. By injecting high frequency voltages the difference of inductance in d and q axis direction can be extracted from the resulting high frequency currents. This information will give the position of the rotor. Problems that will arise are low signal to noise ratio (SNR) on the resulting currents making the measurements sensitive to for example noise and non-linearity in the converter. [10] As the position is determined by the inductance in the rotor there will be problems when the iron becomes saturated as that will decrease the inductance. The problem with saturation is significant in motors for hybrid electric vehicles (HEV) where the torque demand is very high. It is also desirable to achieve a short motor to make it easy to fit. For high torque output, concentrated windings are then needed, increasing the risk for saturation. [9]

II. EXTENDED KALMAN FILTER ALGORITHM

So far only linear systems have been considered. But in practice the dynamic or the observation model can be nonlinear. One approach to the kalman filter for such nonlinear problems is the so called Extended Kalman Filter, which was discovered by Stanley F. Schmidt. After Kalman presented his results about Kalman filtering, Schmidt immediately began applying it to the space navigation problem for the Upcoming Apollo project for manned exploration of the moon. In this process he invented the extended Kalman filter. This Kalman filter linearises about the current estimated state. Thus the system must be represented by continuously differentiable functions. One disadvantage of this version of the Kalman filter for nonlinear systems is that it needs more time consuming calculations. The implementation for linear systems can be made more efficient by pre-computing the dynamic matrix F, the state transition matrix ϕ and the observation matrix H. But for linear systems, these are functions of state and consequently change with every time step and cannot be pre-computed.

There are two steps of algorithm as follows,

[1]. Prediction

[2]. Correction

Prediction:- In nonlinear case the dynamic matrix F is function of state to be estimated. So the predicted state is calculated by solving the differential equations in the form

$$\bar{\underline{x}}\,(t) = f\,(\,\bar{\underline{x}}\,(t)) \qquad (1)$$

By representing this equation by Taylor Series with respect to x at the predicted state $\bar{\underline{x}}$ (ti) and assuming that the higher order terms can be neglected,the dynamic matrix F(ti) can be calculated with

$$F(ti) = {}^{\delta} f(\underline{x}) \,/\, {}^{\delta}x \text{ when } x = x(ti) \qquad (2)$$

And now other steps of the prediction can be calculated, but it should be noted that, now the used matrices are not constant like in the linear case. but depend on the time step.

$$\frac{d}{dt} \phi \, limit(ti \text{ to } ti\text{-}1) = F(ti) \, \phi \, limit(ti \text{ to } ti\text{-}1) \quad (3)$$

Correction:-

Like the differential equations in the prediction step the corresponding linear observation equations are linearized with the Taylor series about the predicted step $\bar{\underline{x}}$ (ti) and higher order terms are neglected.

Thus the approximate observation matrix is

$$H(ti) = {}^{\delta}h(\underline{x}) / {}^{\delta}\,\underline{x} \quad \text{when } \underline{x} = \underline{x}(ti) \qquad (4)$$

In that case the predicted measurement $\bar{\underline{l}}$ (ti) for calculating the measurement residual (l (ti)- $\bar{\underline{l}}$ (ti)) is

$$\bar{\underline{l}}\,(ti)=h \, \bar{\underline{x}}\,(ti) \qquad (5)$$

Further on, we can again use the same formulas to calculate the correct state its covariance matrix like in the linear case but with time dependent matrices.

$$x+(ti) = \bar{x}(ti) +K(l\,(ti)- \bar{\underline{l}}\,(ti)) \qquad (6)$$

And

$$P+(ti) = (I- K(ti)\, H(ti))\, \bar{p}(ti) \qquad (7)$$

With

$$K(ti) = \bar{p}\, H(ti)^{T} (H(ti)\, \bar{p}\, H(ti)^{T}) +Rr(ti))^{-1} \qquad (8)$$

III. HF INJECTION METHOD

Unlikely from original 'true' high frequency (HF) injection method [8], the virtual HF signal is not added to basic supply voltage of inverter, but it is subtracted from it, so acting stator voltage of model [5] as follows:

$$Vsact = Vs- Vinj \qquad (1)$$

The injection- and acting model voltages are virtual, obviously synchronized by real stator voltage. The acting voltage obtained from the model of PMSM causes the virtual acting stator current as response on it. From this response it is possible to extract the information about rotor position even under the rotating motor, by the same way as classical injection method (using filters).

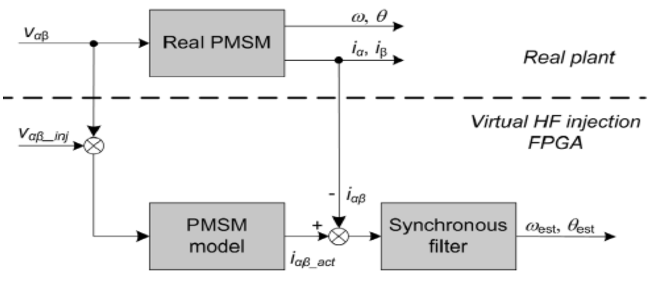

Fig1: Fundamental block diagram of VHFIM method

It is possible to express HF component of actual modeled stator current isinj

$$Isinj = Is- Isact \qquad (2)$$

As it can be seen the overall current consists of two components: positive sequence component and negative sequence component. The negative sequence component is proportional to the differential stator transient inductance and contains useful spatial information, and can be extracted by filtering [8] and [9]. A method used for speed control in simpler control systems is the volts-hertz method. Speed control is achieved by varying the

supply frequency and by controlling the supply voltage approximate proportional to speed, the magnetization in the machine is kept constant. This
Control strategy can be used without any kind of speed or position feedback and is called open loop control. [6] To use open loop control with a synchronous machine the speed has to be varied slowly, this to ensure that synchronism is not lost. [7] The control method used in most high performance PMSM-drives is the field oriented control which allows both torque and speed control with more precision than the volt-hertz method. Field oriented control with rotor flux orientation (RFO) utilizes the fact that the PMSM machine in many ways is similar to a DC-machine turned inside out. By transforming to a coordinate system rotating with the same speed as the rotor, voltages and currents become dc quantities. This is called the synchronous reference frame, or sometimes the direct and quadrature, dq-system. The direct axis, often called d, is aligned with the permanent magnet
flux linked with the stator windings and the quadrature axis, called q, is placed orthogonal from that. The stator current can then be divided into a d-directed, flux producing part and a q-component that produces torque. In the control system it will then be easy to control the magnetization and torque production in the machine independently, just like in a dc machine. The 3-phase quantities are generally expressed in a two-phase stator stationary coordinate system (αβ). The dq-system is then displaced from the αβ-system with the rotor flux angle, θr, as seen in fig2.

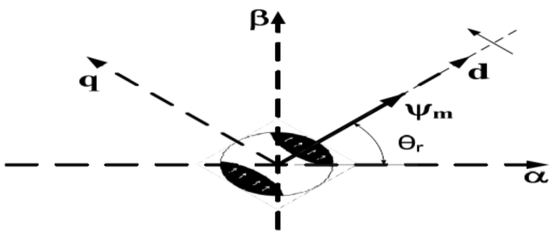

Fig2: definition of the dq and αβ-reference frame

IV. CONCLUSION

In this paper we have seen that for sensorless control two methods are used. HF method is used for low and stand still position considering stator voltage. Extended Kalman Filter algorithm is used for low and high speed.

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