Sensorless Speed Control of Synchronous Reluctance Motors Using Model Predictive Control Associated with Model Reference Adaptive System

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***Abstract*— This paper presents a predictive strategy and Model Reference Adaptive System for the control of a synchronous reluctance motor (SynRM). Our approach allows controlling the speed by associating two estimators of the current magnitudes through the predictive control and the model reference adaptive system. To obtain a predictive control, the most idea is to extract the variables to be controlled from the model of the machine to calculate their next behaviour and to choose the best optimization criterion. The Model Reference Adaptive System uses state observer model with current error feedback and rotor current model as two models for current estimation. The rotor speed is estimated so that the difference between the outputs of state observer model and rotor current model may be zero.**

Keywords*— *Synchronous reluctance motor, Model Predictive control, Model Reference Adaptive System, Sensorless Control, Vector Control.

I. Introduction

Synchronous motors, including synchronous reluctance motors (SynRM), have been widely used because of their high energy efficiency. To realize precise control of these motors, information of rotor position and velocity is necessary [3]. However, position or velocity sensors are expensive and have problems, removing these sensors gives a number of advantages such as increased reliability, lower production costs, reduced size and removal of excess cabling. Sensorless drives require less maintenance and are also more suitable for harsh inaccessible environments, so many sensorless control methods have been proposed. extended Kalman filter (EKF) [9] and high-frequency signal injection methods [8] ,the EEMF model taking into consideration magnetic saturation, is derived and is applied to a position estimation method[7]

In this paper, we propose a new approach to estimating speed by association of two estimators; the first estimator is model predictive control which is based on the prediction of the variables to be controlled, and the subsequent choice of the best value measured by an appropriate cost function [3 [4] [6]. The second estimator is the Model reference adaptive system which have been proven to be one of the best methods being proposed by the researchers due to its good high-performance ability and straight-forward stability approach

The quantification of the angle generates a high amplitude and high frequency noise that affects the good prediction of the estimated speed. In order to overcome this problem, the use of MRAS has been proposed for the estimation of the rotor speed.

II. The machine model

A. Continuous Time Machine Model

The dynamic model of SynRM represented in terms of voltages and currents can be given as:

$$v_{sd}=R_s i_{sd}+L_{ds}\frac{di_{sd}}{dt}-\omega_r\phi_{qs} \tag{1}$$

$$v_{sq}=R_s i_{sq}+L_{qs}\frac{di_{sq}}{dt}+\omega_r\phi_{ds} \tag{2}$$

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix}=\begin{bmatrix} R_s & -L_{qs}\omega_r \\ L_{ds}\omega_r & R_s \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}+\begin{bmatrix} L_{ds} & 0 \\ 0 & L_{qs} \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \tag{3}$$

The speed ω_r in the above equations is related to the torque by the following mechanical dynamic equation,

$$J\frac{d\omega}{dt}=(T_e-T_r)-f\omega \tag{4}$$

ω represents the mechanical speed, T_e the electric torque, T_r the load torque, J the rotor inertia and f the friction coefficient.

Where ω_r is the rotor speed which is defined as

$$\omega_r=p\omega\ ,\ \ \omega=\frac{d\theta}{dt} \tag{5}$$

The electric torque T_e is given by

$$T_e=\frac{3p}{2}(\phi_{ds}i_{qs}) \tag{6}$$

From (3),(4),(5) and (6) the state space for synchronous reluctance motor (SynRM) can be represented as follows:

$$\frac{d\gamma(t)}{dt}=\delta(x(t),u(t)) \tag{7}$$

where

$\gamma\triangleq[i_{sd}\quad i_{sq}\quad \omega]^T$, $u\triangleq[v_d\quad v_q]^T$

$$\delta(\mathrm{x,u})\triangleq\begin{pmatrix} -\frac{1}{T_d}i_{sd}+\omega_r i_{sq}+\frac{1}{L_d}v_d \\ -\frac{1}{T_q}i_{sq}-\omega_r i_{sd}+\frac{1}{L_q}v_q \\ \frac{\frac{3}{2}p(L_{ds}-L_{qs})i_{sd}i_{sq}}{J}-\frac{f}{J}\omega-\frac{T_r}{J} \end{pmatrix} \tag{8}$$

where $T_d=\frac{L_d}{r_s}, T_q=\frac{L_q}{r_s}$ are the stator time constants.

B. Predictive Model

In order to obtain a predictive model for the motor, the model (7) will be discretized. By using the Euler approximation [1] for the stator current derivatives for a sampling time T_s, that is,

$$\frac{di}{dt} \approx \frac{i(k+1) - i(k)}{T_s} \qquad (9)$$

The following expressions for the predicted stator currents in the *dq* reference frame are obtained from (1) and (2):

$$i_{sd}^{p}(k+1) = \left(1 - \frac{R_s T_s}{L_{sd}}\right) i_{sd}(k) + T_s \omega_r i_{sq}(k) + \frac{T_s}{L_{sd}} v_{sd} \quad (10)$$

$$i_{sq}^{p}(k+1) = \left(1 - \frac{R_s T_s}{L_{sq}}\right) i_{sq}(k) - T_s \omega_r i_{sd}(k) + \frac{T_s}{L_{sq}} v_{sq} \quad (11)$$

These equations allow predictions of the stator currents to be calculated for each one of the seven voltage vectors generated by the inverter fig 1.

A variation of PWM is called space vector modulation (SVM), in which the application times of the voltage vectors of the converter are calculated from the reference vector. It is based on the vectorial representation of the three-phase voltages, defined as

$$\vec{v} = \frac{2}{3}\left(\overrightarrow{v_{aN}} + a\overrightarrow{v_{bN}} + a^2\overrightarrow{v_{cN}}\right) \qquad (12)$$

Where v_{aN}, v_{bN} and v_{cN} are the phase-to-neutral (*N*) voltages of the inverter and $a = e^{j2\pi/3}$. The output voltages of the inverter depend on the switching

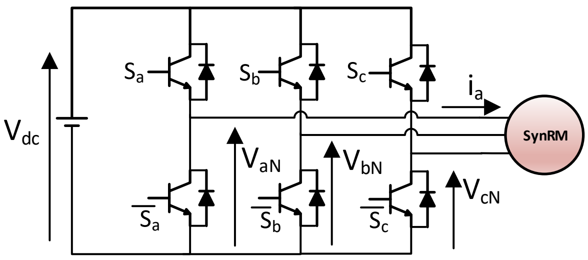

Fig 1. Two level voltage source inverter

state of each phase and the DC link voltage, $v_{xN} = S_x V_{dc}$ with x={a,b,c}.Then , taking into account the combination of the switching states of each phase, the three-phase inverter generates the voltage vectors listed in table 1 below ,

S_a	S_a	S_a	Voltage vector
0	0	0	$V_0=0$
1	0	0	$V_1=\frac{2}{3}V_{dc}$
1	1	0	$V_2=\frac{1}{3}V_{dc}+j\frac{\sqrt{3}}{3}V_{dc}$
0	1	0	$V_3=-\frac{1}{3}V_{dc}+j\frac{\sqrt{3}}{3}V_{dc}$
0	1	1	$V_4=-\frac{2}{3}V_{dc}$
0	0	1	$V_5=-\frac{1}{3}V_{dc}-j\frac{\sqrt{3}}{3}V_{dc}$
1	0	1	$V_6=\frac{1}{3}V_{dc}-j\frac{\sqrt{3}}{3}V_{dc}$
1	1	1	$V_7=0$

Table 1. Switching states and voltage vector

The voltage vectors generated by the inverter are fixed in the stationary reference frame, but they are rotating vectors in the *dq* reference frame, calculated as

$$V_s^{(r)} = V_s e^{-j\theta_r} \quad (13)$$

Using the seven possible inverter voltage vectors as inputs to the discrete model given by (10) and (11), seven different predictions for the system state $\gamma = [i_{sd} \;\; i_{sq} \;\; \omega]^T$ are achieved.

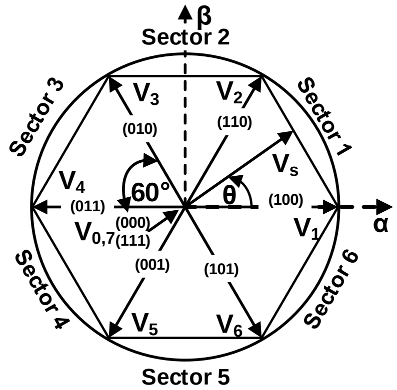

Fig 2. Voltage vectors and sector definition

C. MRAS observer design

MRAS estimators consist of reference model and adjustable model as shown in Fig 3. The speed adaptation laws adjust the estimate speed based on the outputs of reference and adjustable models. So, MRAS used in this model compares both the outputs of a reference and adaptive models, and processes the error between these two based on the appropriate adaptive laws that do not disturb the stability of the applied system [2].

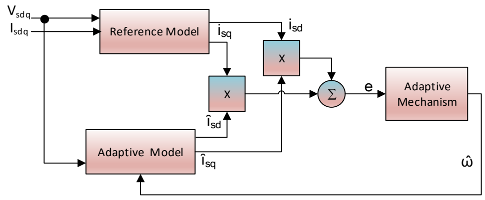

Fig 3. Generalized model reference adaptive system

As it is illustrated in fig 4 that the difference between reference and adaptive model is used to feed a PI controller. The output of the controller is used to tune the adjustable model, which in turn actuates the rotor speed. The speed estimation adaptation law is derived using Lyapunov theory to insure estimation stability.

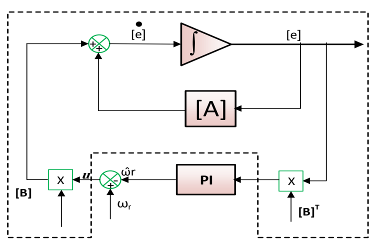

Fig 4. Structure of MRAS

D. Control Scheme

The control of three-phase SynRM is a challenging problem as they exhibit significant nonlinearities and there are chances that parameters may get affected due to variation in various operating condition.

Vector control provides good performance in transient condition in addition to steady state condition [7].

Fig 4 shows Field Oriented Control of a SynRM using predictive and MRAS current control, a PI controller is used for speed control and generates the reference for the torque-producing current i_{sqref} providing from the MRAS speed observer. A predictive current controller is used for tracking this current. In the predictive scheme, the discrete-time model of the machine is used to predict the stator current components for the seven different voltage vectors generated by the inverter. The voltage vector that minimizes a cost function is selected and applied for an entire sampling interval.

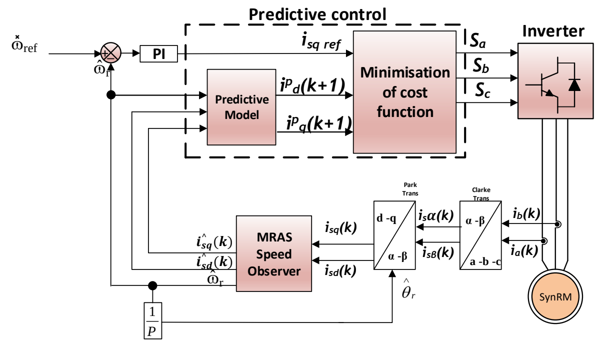

Fig4. a-Foc of a SynRM using predictive and MRAS current control

III. Design of Predictive and MRAS Current Control

A. Predictive design

The objective of the current control system is to minimize the error between the measured currents and the reference values. This objective, in the case of SynRM speed control, can be expressed as a cost function that meets certain requirements such as monitoring the reference speed ,torque by ampere optimization and limiting the current intensity, which is expressed as follows:

$$g=(i^p_{sd}(k+1))^2+(i^{ref}_{sq}-i^p_{sq}(k+1))^2+\hat{f}\,(i^p_{sd}(k+1),(i^p_{sq}(k+1)) \quad (14)$$

where;

- $(i^p_{sd}(k+1))^2$: represents the minimization of the reactive power.
- $(i^{ref}_{sq}-i^p_{sq}(k+1))^2$ is designed to tracking the torque producing current
- $\hat{f}\,(i^p_{sd}(k+1),(i^p_{sq}(k+1))$ is a nonlinear function for limiting the current amplitude stator which defined as:

$$\hat{f}(i^p_{sd}(k+1),(i^p_{sq}(k+1))=\begin{cases}\infty \text{ if } \left|i^p_{sd}\right|>\hat{i}_{sd} \text{ or } \left|i^p_{sq}\right|>\hat{i}_{sq}\\ 0 \text{ if } \left|i^p_{sd}\right|\leq\hat{i}_{sd} \text{ and } \left|i^p_{sq}\right|\leq\hat{i}_{sq}\end{cases} \quad (15)$$

At last, the voltage vector which minimizes the described cost function is selected and applied to the motor at the beginning of every sampling period.

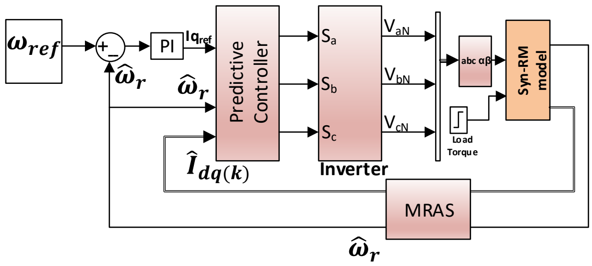

Fig5. b-Foc of a SynRM using predictive and MRAS current control

B. MRAS design

The dynamic model of the SynRM can also be rearranged from equation 1 and 2, so the adjustable model of SynRM is defined as follows

$$\frac{d}{dt}\begin{bmatrix}\hat{i}_{sd}\\ \hat{i}_{sq}\end{bmatrix}=\begin{bmatrix}-\frac{R}{L_d} & \widehat{\omega}_r\\ -\widehat{\omega}_r & -\frac{R}{L_q}\end{bmatrix}\begin{bmatrix}\hat{i}_{sd}\\ \hat{i}_{sq}\end{bmatrix}+\begin{bmatrix}\frac{1}{L_d} & 0\\ 0 & \frac{1}{L_q}\end{bmatrix}\begin{bmatrix}v_{sd}\\ v_{sq}\end{bmatrix} \quad (16)$$

As illustrated in fig 4, the output of MRAS $\hat{x}=[\hat{i}_{sd} \quad \hat{i}_{sq}\ ]^T$ feeds the inner loop that performs predictive current control and $\hat{\omega}$ that handles speed feed the outer loop where the reference current i_{sqref} is obtained from this outer speed control loop

Simulation Results

The proposed predictive strategy associated with Model Reference Adaptive System for the control of a synchronous reluctance motor (SynRM) is obtaining with the MatlabSimulink software . The design criteria for th adaptive PI controller of MRAS is done using root locus method by using the transfer function of the plant and set the time domain constraint which is considered in this design ; percent of overshoot, settling time and rise time are less than 2.09 %, less than 0.0583 second and less than 0.00502 second respectively.

The listed table 1 describing the parameters of our machine was used in this simulation and a sampling period Ts = 10[µs] was used as well as the inverter which is characterized by a DC link of 528[V] and dead-time of 2[µs].

The effect of using MRAS estimator is evident, showing a significant improvement on the estimated speed $\widehat{\omega}_r$ and a good reference speed tracking (figure 6).

The stator currents show low harmonic distortion, which is a consequence of imposing zero reference for i_{sd} (figure 7).

Finally, the control of the current components i_{sd} and i_{sq} is highly decoupled, achieving almost zero i_{sd} current (figure 8).

The simulation results obtaining with the MatlabSimulink software valid our choice. The predictive model, and the evaluation of the cost function, was coded as a MATLAB S-function in the C language for easy migration to an experimental set-up.

TABLE 1. PARAMETERS OF THE SYSTEM USED IN SIMULATION

Parameter	Values
d-axis inductance (L_d)	0.1524 (h)
q-axis inductance (L_q)	0.0345 (h)
Number of pole (p)	2
Friction coefficient (f)	0.00015 ($N.m^{-1}$)
Moment of inertia (J)	0.00044 ($Kg.m^2$)
Stator resistance (R_s)	8.1 (Ω)
d-time constant ($T_d=L_d.R_s^{-1}$)	0.01881 (s)
q-time constant ($T_q=L_q.R_s^{-1}$)	0.00426 (s)

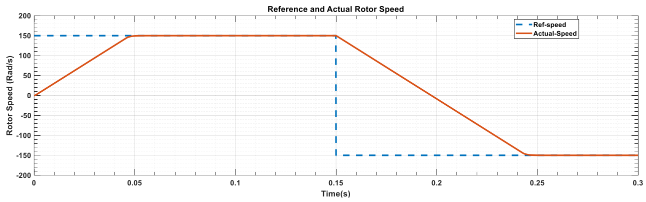

Fig6.Reference and Actual Rotor Speed

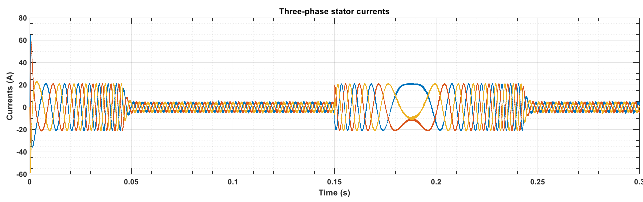

Fig7.Three-Phase Stator currents

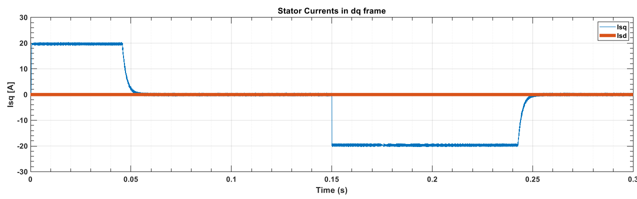

Fig8.Stator Currents in dq frame

CONCLUSION

In this work, a predictive strategy and an adaptive model reference system for the control of a synchronous reluctance motor (SynRM) was proposed. Our objective is to analyze and implement currents controllers as a replacement for classical PI currents controllers and improve the tracking rotor speed to the reference one by introducing the MRAS estimator. Simulation results obtained at a constant speed of 150 rad/s and an inverter switching of 5 KHz pointed out the performance improvements introducing by this approach.

The implementation of the current controller proved to be simple and intuitive. The simulation shows that the controller can generate the correct voltage to reach the reference speed. The discretized model obtained by sampling time approximation used in this work correctly predicts the rotor speed values.

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