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Implementation of sensorless SM-DTC with conjoint online parameters identification based on MRAS

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Abstract

The MRAS based on rotor flux integrated in the direct torque control (DTC-MRAS) is a very good solution in the speed estimation and control of the induction motor without speed sensor, the major problem with this theory is the machine parameters time-varying, which is causing the degradation of the performances and the stability of the drive. In this work, we aim to implement a DTC based on MRAS for rotor speed estimation and the joint online identification of stator resistance (Rs) and the inverse of rotor time constant (1/Tr). The proportional-integral regulators (PI) are used in the mechanism adaptation. Also, a sliding mode controller type is introduced in the speed control loop. For testing the performance and the stability of the proposed methods, an experimental setup is prepared with Simulink environment and the RTI blocs of the dSPACE card (DS1104).

Keywords: DTC, Induction Motor, sliding mode, parameter estimation, dSPACE

1. Introduction

In the middle of the eighty years DTC is initially filed by I. Takahashi and T. Noguchi [1]. It's based mostly on the direct regulation of electromagnetic torque and the stator flux. The DTC is characterized by a good dynamic of the torque response compared to the other types of control systems, but a considerable value of chattering has occurred in different operating conditions due to hysteresis regulators [2]. Besides that, the stator and rotor resistances variation problems also have a great influence on the system stability and the drive [1]. To improve the performance of this method, a lot of work is done, among these works the direct torque control without a mechanical sensor appeared as one of the most used techniques.

The model reference adaptive system (MARS) has appeared in many papers [3], [4] , it's the most methods used sensorless control because of its simplicity of modelling, height stability and facility for implementation. However, the main problems with this technique are the time-varying parameters of the induction machine, also the problem of the pure integration [5]. As a result, the authors in [6] used MRAS theory based on the reactive power for canceling the influence of the stator resistance on the control, but he is but it is strongly felt in the system instability problem. Therefore, the MRAS based on the rotor flux that is offered by Schauder [7] is the most used strategy in the theory, many works were achieved to prove its performance.

In all estimation methods, the problems were located at low speed, because the voltages induced in the rotor are so small and disappear at the zero frequency of stator [8]. To enhance the stability and the system response of the estimation and the control of the rotation speed, and to avoid the problem of the parameters variation of the induction machine, many papers proposed the online identification and correction of stator resistance as in [9], [10] and also the inverse of rotor time constant in [11], [12].

The proportional-integral regulators are broadly used in the implementation of industrial control systems of induction machines. They are extensively used in the field of regulation and particularly in industrial systems. Because of their simple design and ease of implementation. Accordingly, the most adaptive systems described for MRAS use a proportional integral regulator (PI) in the mechanism adaptation of the error between the adaptive and reference model for the estimation of the rotor speed and the motor parameters [7], [10], [12].

Due to the problem of the chattering produced in the torque and flux in the control and also the integration problem of the PI [13], we have introduced a regulator based on sliding mode theory in the rotor speed closed loop. This control (SMC) is assumed to be a discontinuous control technique which presents a number of advantages over the classic controller; it provides an easy implementation, more stability of the system and faster response [14].

In this work, we suggest replacing the conventional PI controllers which are used in the estimated speed adaptation by a sliding mode controller accompanied by an online joint identification of the parameters of the induction machine, to improve the robustness and high dynamics of the SM-DTC control without speed sensor.

2. DTC with speed sliding mode control

2.1. The DTC theory

Generally the principle of DTC control is the estimation and the control of the electromagnetic torque and the stator flux. It is feasible with the help of the hysteresis controller, which determines the inverter switching state. The stator flux of the machine is defined by:

$$\frac{d}{dt}\varphi_s = V_s - R_s I_s$$
$$\varphi_s = \varphi_{s0} + \int_0^t \left(V_s - R_s I_s\right)dt \qquad (1)$$

$$J\frac{d\Omega}{dt} = T_e - T_r - f_v\Omega \qquad (2)$$

Rs, Rr : The stator and rotor resistances. J: The moment of inertia. : The mechanical rotor speed. Te, Tr The electromagnetic and load torques. fv : The viscous friction coefficient

One can consider the voltage drop is negligible compared to Vs; the trajectory of the vector connected to the vector voltage Vs the output of the inverter.

$$\varphi_s(t+\Delta t) = \varphi_s(t) + V_s.\Delta t \qquad (3)$$

Where (t+Δt) is the time deduced from the vector at the time t. The torque is described as:

$$T_e = K_c.\vec{\varphi}_s.\vec{\varphi}_r.\sin(\delta_0) \qquad (4)$$

Where Kc is a machine constant. Presumably, the stator flux follows its reference; the torque can then be described then as:

$$T_e = K_c.\varphi_{sref}.\varphi_r.\sin(\delta_0) \qquad (5)$$

The electromagnetic torque (t+Δt) is:

$$T_e = K_c.\varphi_{sref}.\varphi_r.\sin(\delta_0 + \Delta\delta) \qquad (6)$$

So, it is necessary to maintain the controlled variables inside the hysteresis controller bands. And the voltage vector applied to each switching time is obtained at the output of the Logic table of Takahashi [1].

2.2. Speed controller based on sliding mode

The SM technique is to cause the path of a state system to the sliding surface and to switch by means of a suitable switching logic around it toward the equilibrium, hence the sliding mode phenomenon occurs [15]. The conditions of convergence enable a dynamic system to converge to the sliding surfaces. We learned from the literature two conditions; these correspond to the convergence mode of the system state [16].

$$S\left(x\right)\dot{S}\left(x\right) < 0 \qquad (7)$$

This is to do scalar function V(x)> 0 for the System's state variables. This function is usually used to assure the stability of the drive. The Lyapunov's function is defined by

$$V\left(x\right) = \frac{1}{2}S^2(x) \qquad (8)$$

The speed surface is defined by:

$$S(x) = \Omega^* - \Omega \qquad (9)$$

The derivative of S(x) is:

$$\dot{S}(x) = \dot{\Omega}^* - \dot{\Omega} \qquad (10)$$

By replacing (2) in (10) and introducing the equivalent control. $T_e = T_{eeq} + T_{en}$ we will have:

$$T_{eeq} = J(\dot{\Omega}^* + \frac{T_r}{J} + \frac{f_v}{J}\Omega) \qquad (11)$$

During the sliding phase and steady state $\dot{S}(x) = 0$ *and* $T_{en} = 0$

$$\dot{S}(x) = \dot{\Omega}^*(\frac{1}{j}(T_{eeq} + T_{en}) - \frac{T_r}{j} - \frac{f_v}{j}\Omega) \qquad (12)$$

The action of the discontinuous control T_{en} is defined during the phase reached, and is as mentioned above satisfy the condition $S\left(x\right)\dot{S}\left(x\right) < 0$, by replacing (12) in (11) we result:

$$\dot{S}(x) = \frac{1}{J}T_e \qquad (13)$$

Where T_{eeq} present the equivalent control which ensures the correct trajectory of the controlled state of the sliding surface and T_{en} present the switchin control which depends on the "sign" function of theswitching phase:

$$T_{en} = K.sign(S(x)) \qquad (14)$$

Where (K>0) is a control gain Therefore:

$$T_e^* J(\dot{\Omega}^* + \frac{T_r}{J} + \frac{f_v}{J}\Omega) + K.sign(S(x)) \qquad (15)$$

3. The rotor speed and parameters estimation based on mras

The principle of the flux-based MRAS technique [7] is to minimize the error between the adjuster and the reference model by an adaptive mechanism that gives the rotor speed as it is presented on figure 1. As in [7][10] the equations (16) (17) present the components of the reference flux which is given by the reference model:

$$p\varphi_{r\alpha} = \frac{L_r}{M}(V_{s\alpha} - \hat{R}_s I_{s\alpha} - \delta L_s p I_{s\alpha}) \qquad (16)$$

$$p\varphi_{r\beta} = \frac{L_r}{M}(V_{s\beta} - \hat{R}_s I_{s\beta} - \delta L_s p I_{s\beta}) \qquad (17)$$

Where: p = $\frac{d}{dt}$. The adaptive or current model exposes the components of the flux which is depending the stator current components and the rotation speed which is the estimated state in this case [8].

$$p\hat{\varphi}_{r\alpha} = \frac{M}{\hat{T}_r} I_{s\alpha} - \frac{1}{\hat{T}_r}\hat{\varphi}_{r\alpha} - \hat{\omega}_r \hat{\varphi}_{r\beta} \qquad (18)$$

$$p\hat{\varphi}_{r\beta} = \frac{M}{\hat{T}_r} I_{s\beta} - \frac{1}{\hat{T}_r}\hat{\varphi}_{r\beta} + \hat{\omega}_r \hat{\varphi}_{r\alpha} \qquad (19)$$

For improving the stability of the system, a conventional PI regulator is utilized in the mechanism adaptation to minimize the error which is expressed by:

$$e_{\omega_r} = \hat{\varphi}_{r\alpha}\varphi_{r\beta} - \hat{\varphi}_{r\beta}\varphi_{r\alpha} \qquad (20)$$

$$\omega_r = e_{\omega r}(k_p + \frac{K_i}{p}) \qquad (21)$$

The MRAS structure used in this paper represented the joint online estimation of the both parameters Rs and Tr, which is adapted to the principle of the hyper-stability [12].

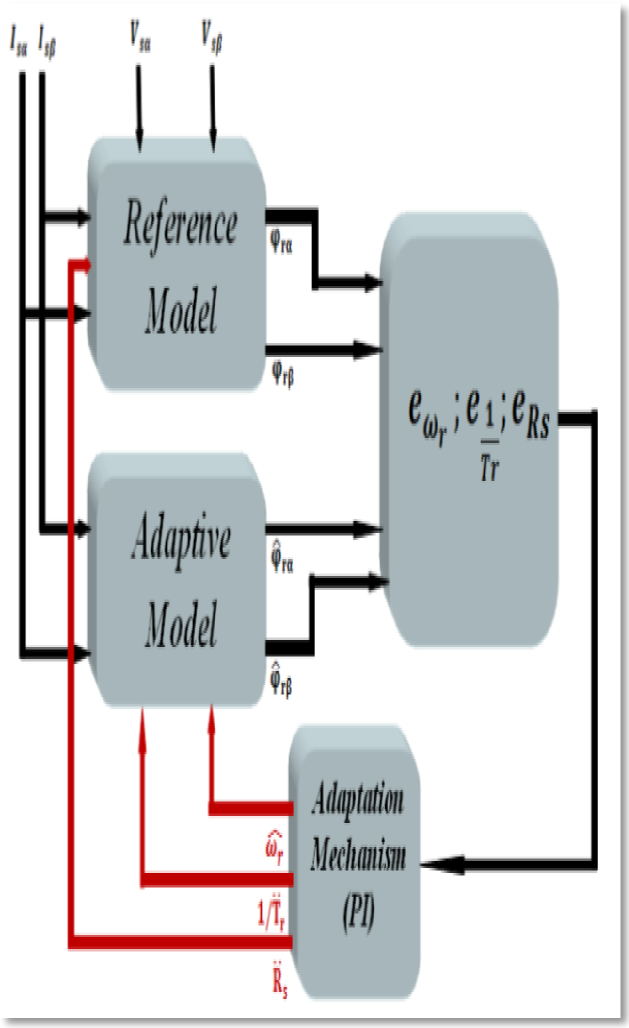


Figure 1. Functional diagram of the MRAS

As in [13] the error equations for the estimation of the inverse of the rotor-time constant is given by:

$$e_{\frac{1}{Tr}} = I_{s\alpha}(\hat{\varphi}_{r\alpha} - \varphi_{r\alpha}) + I_{s\beta}(\hat{\varphi}_{r\beta} - \varphi_{r\beta}) \qquad (22)$$

In the stator resistance estimation we use the same equations, but with a change of role between the two models that the reference model has become an adjustable model and otherwise as in [11], the error is given by:

$$e_{Rs} = I_{s\alpha}(\varphi_{r\alpha} - \hat{\varphi}_{r\alpha}) + I_{s\beta}(\varphi_{r\beta} - \hat{\varphi}_{r\beta}) \qquad (23)$$

The adaptation mechanisms that minimize the error between the two models are based on proportional integral controller.

The figure 2 presents the functional diagram of the DTC Control uses the sliding mode controller and use an MRAS technique for the rotation speed estimation and the joint online parameters (Rs, Tr) identification

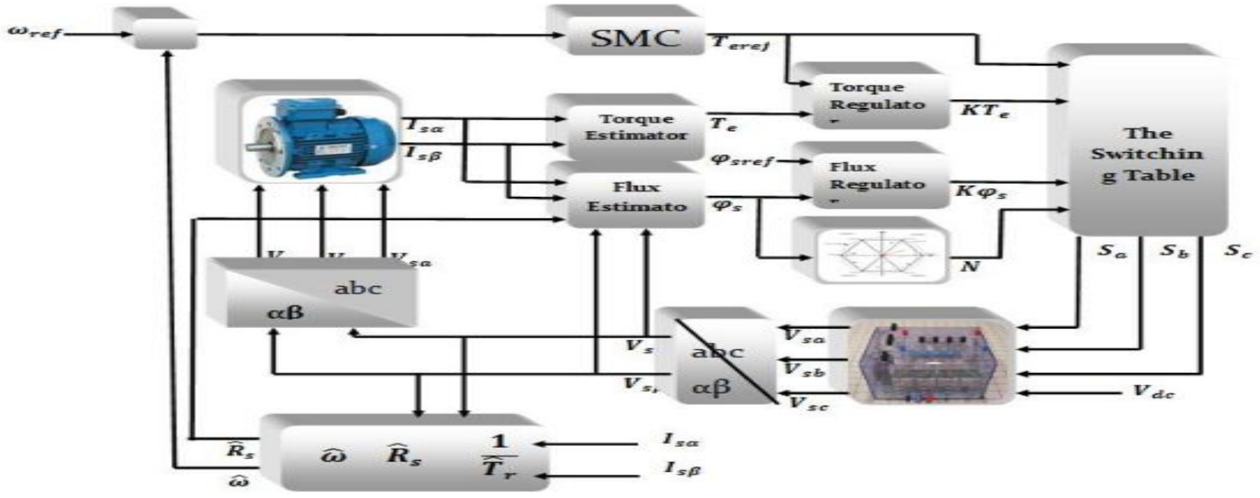


Figure 2. Functional diagram of the DTC

4. Experimental implementation

The experimental testing presented in figure 3 is composed of a squirrel cage induction motor: 2880 rpm, 230/400V, 4/2.8A, 1 kW. The motor is loaded by a DC 1kW generator with a resistive load. The drive is implemented on the DS1104 card using the Simulink and real time interface block. Current sensors with Hall Effect sare used to measure the phase currents; the induction motor is coupled with a 1024 pt incremental encoder for the rotor speed measure. The lowpass filter is a good solution to minimize the chattering of the reference torque obtained from the sliding mode controller. The using of low cut-off frequency reduces torque ripples, but introduces more delay in the dynamic response of the system. A 60 Hz frequency was found to be a good compromise between the reduction of torque ripple and the improvement of the system response. The values of the PI regulator for speed estimator MRAS are: Kp = 20.15 and Ki = 7076, the sampling times used is Ts =100 ms and solved by the Euler method. The electrical and mechanical parameters of the induction machine were identified by conventional methods presented in table 1

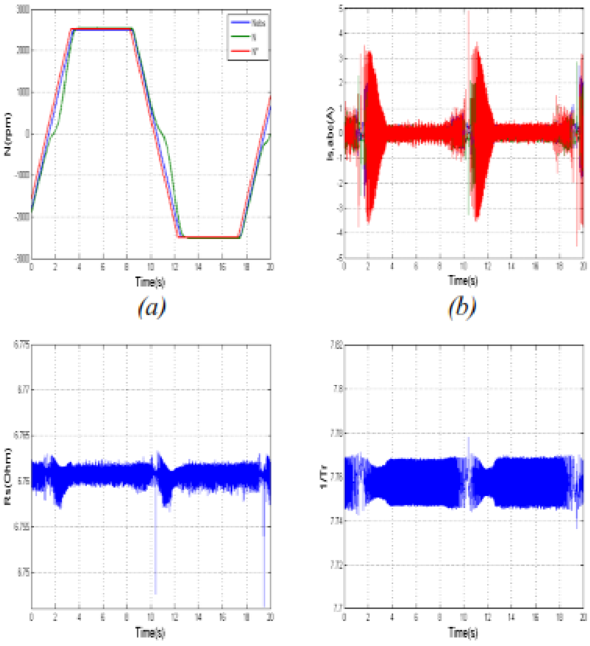
Table1: The machine parameters

Variable	**Value**	**Variable**	**Value**
Number of pair pole	1	Rotor inductance	0.7490 H
Stator resistance	6.58Ω	Mutual inductance	0.7209 H
Rotor resistance	5.81Ω	moment of inertia	0.00207kg.m^2
Stator inductance	0.7490 H	viscous friction coefficient	0.000173N.m/(rad/s)

Figure 3. The experimental test table

4.1. Performance of the SM-DTC

A trapezoidal speed reference varying between -2500rpm and 2500 rpm is used, when the motor is working without load torque.



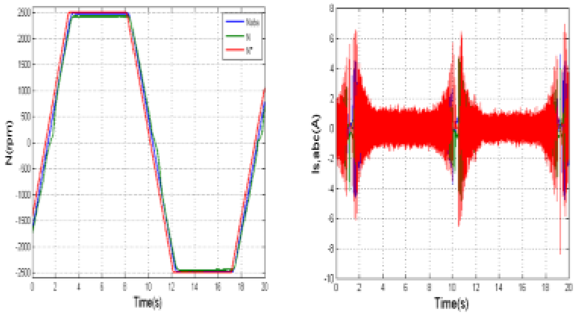
(a) *(b)*

(c) *(d)*

Figure 4. The SM-DTC with speed and parameters estimation at noload torque

The observed and actual speeds presented in figure 4.a followthe reference without overshoot neither static error, duringthe zero crossing one can note a little delay in the dynamicresponse in the actual speed compared to the estimatedspeed. In figure 4.b, a small peak is appeared in the stator currents. The joint online estimation of the stator resistance presented in the figure 4.c and the inverse of the rotor time constant presented in figure 4.d is stable even the reference variation.

The figure 5 present the performances of the drive, where the speed follows the same trapezoidal reference with a half load of the rated torque.



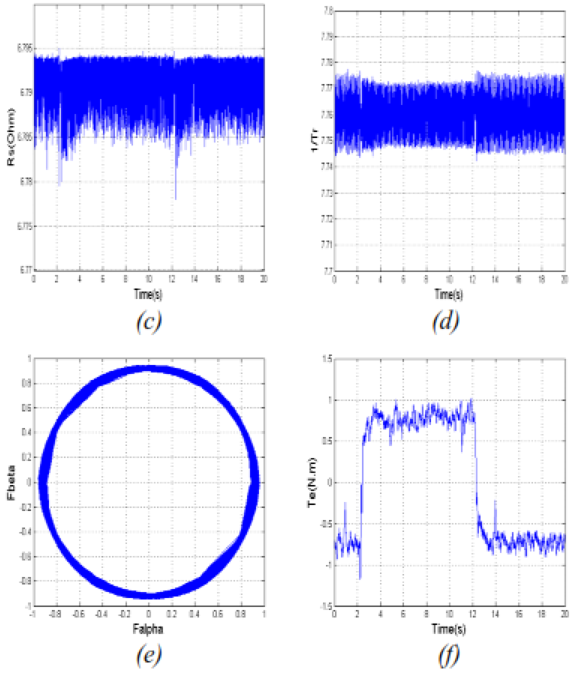
(a) *(b)*

Figure 5. SM-DTC with speed and parameters estimation with a halfload of rated torque

As remarked, the estimated and the measured speed presented in figure 6.a follow his trapezoidal reference, in figure 6.f, the torque presents a high dynamic response, and thestator flux in figure 6.e. presents a circular trajectory. In addition, thefigures figure 6.c and figure 6.d shows that the online estimation of the induction machine parameters is always stable even inthe dynamic regime.

4.2. The performances at low speed

To check the dynamic response and the stability of the SMMRAS, we used a step reference changing between 500 rpm and -500 rpm, the motor is working at low speed with load torque.



(c) *(d)*

(e) *(f)*

Figure 6. The low speed control with half load of the rated torque

At half load of rated torque, one can see that the chatteringis reduced in the stator currents (figure 6.b), the estimatedparameters (figure 6.c, figure 6.d), and the measured speed(figure 6.a). The observed and actual speed follows theirreference with a little overshoot during the speed reverse,the torque (figure 6.f) present a highly dynamic, and the flux(figure 6.e) has a circular trajectory. Generally the controlpresents a good stability and robustness at te low speed drive.

5. Conclusion

In this research, we presented the experimental implementation of SM-DTC induction motor control without speed sensor with a joint on-line estimation of thestator resistance and the rotor time constant. The results show a good speed tracking performance with simplicity ofthe experimental realization. But we found a chatter problem in the current and the estimated parameters, especially at low speed, and also a small problem of integration at the mechanical adaptation with (PI) of theMRAS. So, that leads us in the future to use more stable regulators as second order sliding mode and artificial neural networks in the regulation of rotor speed and parameter estimation respectively

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