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Model reference adaptive backstepping control of double star induction machine with extended Kalman sensorless control

Introduction. *Newly, the design of a controller for speed control of double star induction motor as a research focus. Consequently, backstepping technique is used to recursively construct a stable control law for speed and flux. Nevertheless, this control law coming from backstepping requires the knowledge of speed and flux values; in practice the measurement sensors are expensive and fragile.* ***The novelty*** *of this work consists to propose a control strategy which based on accurate Kalman filter observer that estimates speed, flux and torque. This extended Kalman filter is an optimal state estimator and is usually applied to a dynamic system that involves a random noise environment.* ***Purpose.*** *Apply a backstepping control of double star induction motor based on principle of rotor flux orientation. This approach consists in finding a Lyapunov function that allows deducing a control law and a modified adaptation rule is referred and sufficient conditions for the stability of the command-observer, in contrast to other techniques who use nonlinear principle.* ***Results.*** *The simulation results are shown to illustrate the performance of the proposed scheme under parametric uncertainties by simulation on MATLAB. The obtained results showed the robustness of the sensorless control in front of load and parameters variation of double stator induction motor. The research directions of the model were determined for the subsequent implementation of results with simulation samples.* References 17, tables 1, figures 18.
Key words: **double stator induction motor, model reference, backstepping control, extended Kalman filter.**

Вступ. *Новітня розробка контролера для регулювання швидкості асинхронного двигуна з подвійною зіркою є предметом дослідження. Отже, метод відступу використовується для рекурсивної побудови стабільного закону керування швидкістю та потоком. Тим не менш, цей закон керування, що випливає з відступу, вимагає знання значення швидкості та потоку; на практиці вимірювальні датчики коштовні та недовговічні.* ***Новизна*** *даної роботи полягає в тому, щоб запропонувати стратегію управління на основі точного спостерігача за фільтром Калмана, який оцінює швидкість, потік і крутний момент. Цей розширений фільтр Калмана є оптимальним засобом оцінки стану і зазвичай застосовується до динамічної системи, яка включає середовище випадкових шумів.* ***Мета***. *Застосування підходу відступу до керування асинхронним двигуном з подвійною зіркою на основі принципу орієнтації потоку ротора. Цей підхід полягає у знаходженні функції Ляпунова, яка дозволяє вивести закон керування та модифіковане правило адаптації, а також достатні умови для стабільності спостерігача команд, на відміну від інших методик, які використовують нелінійний принцип.* ***Результати***. *Результати моделювання наведені для ілюстрації роботи запропонованої схеми за параметричних невизначеностей шляхом моделювання на MATLAB. Отримані результати показали надійність безсенсорного керування перед зміною навантаження та параметрів асинхронного двигуна з подвійним статором. Визначені напрямки дослідження моделі для подальшої реалізації результатів на прикладах моделювання.* Бібл. 17, табл. 1, рис. 18.
Ключові слова: **асинхронний двигун з подвійним статором, еталонна модель, керування на основі відступу, розширений фільтр Калмана.**

Introduction. Recently, the double star induction motor (DSIM) has been widely used in various industrial applications due to its high reliability, relativity low cost, segment the power and easy maintenance requirements [1]. However, its nonlinear structure requires decoupled torque and flux control. Several methods of control are used to control the double star induction motor among which the field orientation control (FOC) that allows a decoupling between the flux and the torque in order to obtain an independent control of the flux and the torque like DC motors.

However, the control of dynamical systems in presence of uncertain and disturbances is a common problem, broadly speaking, process control refers to mechanisms for automatically maintaining the conditions of a mechanical, or electrical process at specified levels and to counteract random disturbances caused by external forces. Recently, several nonlinear control approaches have been introduced to control speed, flux and currents as backstepping control; and adaptive control which taking into account the effect of disturbances (varying parameters).

The process control is «adaptive» in the sense that it changes its output in response to a change in the error. A truly adaptive controller adapts not only its output, but its underlying control strategy as well. It can tune their own parameters or otherwise modify its own control law so as to accommodate fundamental changes in the behavior of the process. Hundreds of techniques for adaptive control have been developed for a wide variety of academic, military, and industrial applications, for example, MRAS (Model Reference Adaptive System), RST (Tracking Simplify Return) and M.I.T rule (Massachusetts Institute of Technology). Arguably the first rudimentary adaptive control scheme was implemented in the late 1950s using a custom-built analog computer (Kalman, 1958). Many «self-tuning» and «auto-tuning» techniques have been developed since then to automate the tuning procedures [2].

MRAS is an important adaptive controller. It may be regarded as an adaptive servo in which the desired performance is expressed in terms of a reference model, which gives the desired response to control signal; this is a convenient way to give specification for a servo problem. Indeed, most commercial controllers today namely model reference adaptive control system has proved very popular on account of a readymade, but heuristically based, rule for synthesizing the adaptive loops called «M.I.T. rule».

A theoretical analysis of loops so designed is generally very difficult, but at present, may be avoided if such systems are synthesized or redesigned on the basis of Lyapunov theory applied to the stability of the adaptive step response [3].

Because the dynamic structure of DSIM is strongly non-linear and coupled. The situation changes with the appearance of the theory of non-linear systems in control theory where the researchers are interested in new control as backstepping control method allow for approaching large systems with a systematic approach, which was introduced during the 1990s by several researchers, Kokotovic is quoted [4]. The application of the latter is found, for example, in the field of aeronautics in [4], and in the field of robotics in [5], and electrical machines [6], and also for power network power regulation in [7].

The majority of the control laws of induction machines such as vector and non-linear commands require the measurement not only of the stator currents (possibly stator voltages) but also of the mechanical speed. Moreover, the load torque is a measurable disturbance but the price of the sensor often makes this measurement unrealistic. The control without the mechanical sensor (speed, load torque) has become a major concern in the industry [8].

Among several approaches without mechanical sensor of the induction machine used neural networks [9], adaptive sliding mode [10], another approach widely used based on a model of behavior of the machine which is based on observation techniques from the extended Luenberger filters in [11, 12], which so with the presence of noise the error of estimations can't be equal to zero. This one decreases the performance of the observer. It is even possible to filter the output in order to eliminate the noise, but this filter can also eliminate its own information of the dynamic of the system, and generally complex to realize.

The goal of the paper is regulate the speed, flux, currents of double star induction motor by hybrid control «Model Reference Adaptive Backstepping Control» coupled by Kalman filter.

Basic calculation relationships and assumptions. The machine to be studied is of the induction type. It is formed of a stator consisting of two three-phase windings mounted in a star shifted by an electric angle *α*. The latter is equal to 30°. The rotor is formed either of a short-circuited three-phase winding or a squirrel cage. It is modeled by a short-circuited three-phase winding. The application of Park transformation to the model of the double star induction machine leads to equations expressed in a frame related to the rotating field (*d*, *q*) by [1, 13-15]. The mechanical equation is given by:

$$\frac{J}{p}\cdot\frac{\mathrm{d}\Omega}{\mathrm{d}t}=T_e-T_L-\frac{B_\omega}{p}\cdot\Omega \quad (1)$$

with the expression of electromagnetic torque T_e:

$$T_e=p\cdot\frac{L_m}{L_m+L_r}\cdot\left[\Phi_{dr}\cdot\left(i_{qs1}+i_{qs2}\right)-\Phi_{qr}\cdot\left(i_{ds1}+i_{ds2}\right)\right]; \quad (2)$$

$$\begin{cases}\Phi_{ds1}=L_{s1}i_{ds1}+L_m[i_{ds1}+i_{ds2}+i_{dr}];\\ \Phi_{qs1}=L_{s1}i_{qs1}+L_m[i_{qs1}+i_{qs2}+i_{qr}];\\ \Phi_{ds2}=L_{s2}i_{ds2}+L_m[i_{ds2}+i_{ds1}+i_{dr}];\\ \Phi_{qs2}=L_{s2}i_{qs2}+L_m[i_{qs1}+i_{qs2}+i_{qr}];\\ \Phi_{dr}=L_ri_{dr}+L_m[i_{ds1}+i_{ds2}+i_{dr}];\\ \Phi_{qr}=L_ri_{qr}+L_m[i_{qs1}+i_{qs2}+i_{qr}].\end{cases} \quad (3)$$

Equations of the stator and rotor voltages are:

$$\begin{cases}v_{ds1}=R_{s1}i_{ds1}+\dfrac{d\Phi_{ds1}}{dt}-\omega_s\Phi_{qs1};\\ v_{qs1}=R_{s1}i_{qs1}+\dfrac{d\Phi_{qs1}}{dt}+\omega_s\Phi_{ds1};\\ v_{ds2}=R_{s2}i_{ds2}+\dfrac{d\Phi_{ds2}}{dt}-\omega_s\Phi_{qs2};\\ v_{qs2}=R_{s2}i_{qs2}+\dfrac{d\Phi_{qs2}}{dt}+\omega_s\Phi_{qs1};\end{cases} \quad (4)$$

$$\begin{cases}v_{dr}=R_ri_{dr}+\dfrac{d\Phi_{qr}}{dt}-\left(\omega_s-\omega_r\right)\Phi_{qr}=0;\\ v_{qr}=R_ri_{qr}+\dfrac{d\Phi_{qr}}{dt}-\left(\omega_s-\omega_r\right)\Phi_{dr}=0.\end{cases} \quad (5)$$

where v_{ds}, v_{qs}, v_{qr}, v_{dr} are the stator and rotor voltages *d-q* axis components; i_{ds}, i_{qs}, i_{qr}, i_{dr} are the stator and rotor currents *d-q* axis components; Φ_r, Φ_s are the stator and rotor fluxes; Φ_d, Φ_q are the stator fluxes *d-q* axis components; ω_r, ω_s, ω^*_{sr} are the stator and rotor pulsation respectively and speed sleep reference; Φ^*_r is the rotor flux control reference; R_r, R_s are the rotor and stator resistances; T_L is the load torque; Ω is the mechanical speed; L_s, L_r, L_m are the stator and rotor inductance, and the mutual inductance respectively; *J* is the total inertia; B_ω is the friction coefficient; *p* is the number of pole pairs.

Indirect field oriented control of DSIM. The difficulty in controlling a dual stator induction machine lies in the fact that there is a strong coupling between the input and output variables and the internal variables of the machine such as flux, torque and speed. Conventional control methods such as torque control by frequency slip and flux ratio of voltage to frequency, can тще ensure significant dynamic performance. The development of electronics at the level in the use of static and semi-conductive converters has allowed the application of new control algorithms such as the vector control which is based on the decoupling of flux and torque.

The principle of the vector control called control by flux orientation, obtained by the adjustment of torque by a component of the current and the flux by the other component. Vector control leads to high industrial performance of induction drives. If we make the rotor flux coincide with the axis (*d*) of the frame linked to the rotating field. The rotor flux orientation by:

$$\Phi_{dr}=\Phi_d;\quad \Phi_{qr}=0\,, \quad (6)$$

where the electromagnetic torque in every moment given by:

$$T_e=p\cdot\frac{L_m}{L_m+L_r}\left(i_{qs1}+i_{qs2}\right)\Phi_r\,. \quad (7)$$

So the main objective in [1, 12] is to produce reference voltages for the static voltage converters supplying the DSIM. Note X^* for reference quantities, (torque, flux, voltages and currents). Applying the orientation of the rotor flux on the system of equations of the machine leads to [12-15] has been presented by ω^*_{sr} the slip angular frequency:

$$\begin{cases} \omega_s^* = \omega_{sr}^* + \omega_r; \quad T_r = \dfrac{L_r}{R_r}; \\ \Phi_r^* = L_m\left(i_{ds1} + i_{ds2}\right); \\ T_e = p \cdot \dfrac{L_m}{L_m + L_r}\Phi_r^*\left(i_{qs1} + i_{qs2}\right); \\ \omega_{sr}^* = \dfrac{R_r L_m}{\left(L_m + L_r\right)\Phi_r^*}\left(i_{qs1}^* + i_{qs2}^*\right) \end{cases} \tag{8}$$

$$\begin{cases} V_{ds1}^* = R_{s1}i_{ds1} + L_{s1}\dfrac{di_{ds1}}{dt} - \omega_s^*\left[L_{s1}i_{qs1} + T_r\Phi_r^*\omega_{sr}^*\right] \\ V_{ds2}^* = R_{s2}i_{ds2} + L_{s2}\dfrac{di_{ds2}}{dt} - \omega_s^*\left[L_{s2}i_{qs2} + T_r\Phi_r^*\omega_{sr}^*\right] \\ V_{qs1}^* = R_{s1}i_{qs1} + L_{s1}\dfrac{di_{qs1}}{dt} + \omega_s^*\left[L_{s1}i_{ds1} + \Phi_r^*\right] \\ V_{qs2}^* = R_{s2}i_{qs2} + L_{s2}\dfrac{di_{qs2}}{dt} + \omega_s^*\left[L_{s2}i_{ds2} + \Phi_r^*\right] \end{cases} \tag{9}$$

Equations (9) constituted the reference equation voltage system.

Structure of the MRAS. The MRAS has proved to be one of the most popular methods in the growing field of adaptive control, particularly for practical application to devices such as autopilots, electrical engineering, where rapid adaption is required [3]. The system has an ordinary feedback loop composed of the process and the controller and another feedback loop that changes the controller parameters (identification algorithm).

The parameters are changed on the basis of feedback from the error, which the difference between the output of the system and the output of the reference model. The ordinary feedback loop is called the inner loop, and the parameters adjustment loop is called the outer loop (Fig. 1).

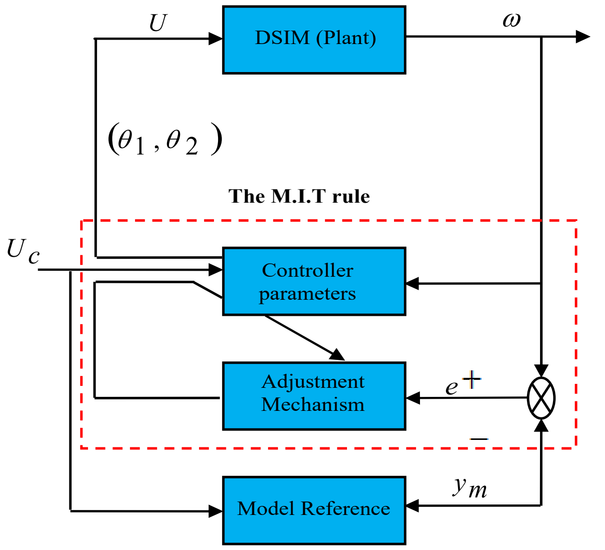

Fig. 1. Diagram of a MRAS based the M.I.T rule

The mechanism for adjustment the parameters in the MRAS can be obtained in two ways: by using a gradient method or by applying stability theory [2].

The M.I.T rule. There is the original approach to MRAS, the name is derived from the fact that was developed at the Instrumentation Laboratory at M.I.T «Massachusetts Institute of Technology» during 1960s [2].

In the MRAS the desired behavior of the system is specified by a model and the parameters of the controller are adjusted based on the error. Let's e be the error between the output y the closed loop system and the desired closed loop response specified by a model whose output is y_m.

One possibility is to adjust parameters θ in such a way that loss function $\Im(\theta) = 0.5e^2$ is minimized.

To make $\Im$ small, it is reasonable to change the parameters in the direction of the negative gradient of $\Im$, that is:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = -\gamma\frac{\partial\Im}{\partial\theta} = -\gamma e\frac{\partial e}{\partial\theta}. \tag{10}$$

And the gradient method gives:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = -\gamma\frac{\partial e}{\partial\theta}\mathrm{sign}e. \tag{11}$$

Generally the version of this algorithm is used in telecommunications, in which a simple implementation and a fast calculation are necessary [2], but in the application of machine controls the Lyapunov theory will be used.

Design of MRAS using Lyapunov theory for DSIM machine. We find a Lyapunov function and an adaptation mechanism such that the error will go to zero. When using the Lyapunov theory for adaptive systems, we find that $\mathrm{d}V/\mathrm{d}t$ is usually only negative semi definite. The procedure is to determine the error equation and a Lyapunov function with a bounded second derivative [3].

The desired response is given by:

$$\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = -a_m\omega_m + b_m\omega_r^*, \tag{12}$$

where a_m>0 and the reference speed ω^*_r is bounded.

The speed equation is described by (4) when $a = \dfrac{B_\omega}{J}$, $b = -\dfrac{1}{j}$, $U = T_e^* - \hat{T}_L$, Note $\hat{X}$ for estimated values $\left(\hat{\phi}_r, \hat{\omega}, \hat{T}_L\right)$ by Kalman filter:

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = -a\omega + bU. \tag{13}$$

The controller is:

$$U = \theta_1\omega_r^* - \theta_2\hat{\omega} \tag{14}$$

introduce the error: $e = \hat{\omega} - \omega_m$

Since we are trying to make the error small, it is natural to derive a deferential equation for the error. We get:

$$\frac{\mathrm{d}e}{\mathrm{d}t} = -a_m e - \left(b\theta_2 + a - a_m\right)\hat{\omega} + \left(b\theta_1 - b_m\right)\omega_r^*.$$

The error goes to zero if the parameters are equal to the value given by:

$$\theta_1^0 = \frac{b_m}{b}, \quad \theta_2^0 = \frac{a - a_m}{b}. \tag{15}$$

Practically these values (J, B_ω) are not real since, and they vary according to the cruel environmental conditions, therefore it can required to update to correct the online value, for this purpose, assume that γ>0 and introduce the following quadratic function [1]

$$V(e,\theta_1,\theta_2) = \frac{1}{2}\left[e^2 + \frac{1}{b\gamma}\left(b\theta_2 + a - a_m\right)^2 + \frac{1}{b\gamma}\left(b\theta_1 - b_m\right)^2\right]. \tag{16}$$

This function is zero when e is zero and the controller parameters are equal to the correct values.

For the function to qualify as a Lyapunov function the derivative $\mathrm{d}V/\mathrm{d}t$ must be negative. The derivative is:

$$\frac{\mathrm{d}V}{\mathrm{d}t}=e\frac{\mathrm{d}e}{\mathrm{d}t}+\frac{1}{\gamma}\left[(b\theta_2+a-a_m)\frac{\mathrm{d}\theta_2}{\mathrm{d}t}+(b\theta_1-b_m)\frac{\mathrm{d}\theta_1}{\mathrm{d}t}\right]=$$

$$=-a_m e^2+\frac{1}{\gamma}(b\theta_2+a-a_m)\left(\frac{\mathrm{d}\theta_2}{\mathrm{d}t}-\gamma\hat{\omega}e\right)+$$

$$+\frac{1}{\gamma}(b\theta_1-b_m)\left(\frac{\mathrm{d}\theta_1}{\mathrm{d}t}+\gamma\omega_r^*\hat{\omega}\right).$$

If the parameters are updated as:

$$\begin{cases}\dfrac{\mathrm{d}\theta_1}{\mathrm{d}t}=-\gamma\omega_r^* e;\\ \dfrac{\mathrm{d}\theta_2}{\mathrm{d}t}=\gamma\hat{\omega}e,\end{cases}\qquad(17)$$

we get $\mathrm{d}V/\mathrm{d}t=-a_m e^2$.

The derivative of V with respect to time is thus negative semi-infinite this implies the error e will go to zero. A diagram of the system is shown in Fig. 2.

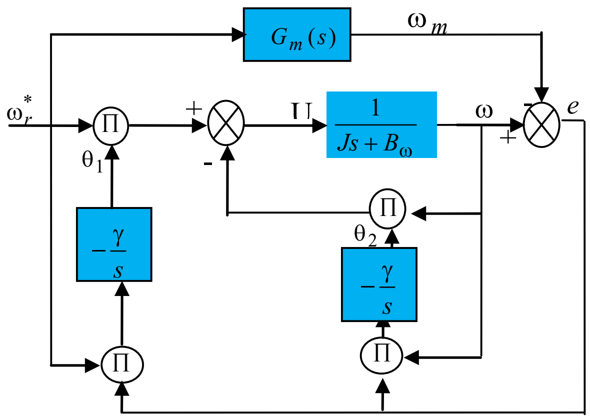

Fig. 2. Diagram of MRAS based on Lyapunov theory for DSIM

Backstepping control of the DSIM. The backstepping control technique provides a systematic method for designing a controller for nonlinear systems [6, 7]. The idea is to compute a control law in order to guarantee, for a certain positive definite (Lyapunov) function, an always negative derivative.

The method consists in breaking up the system into a set of decreasing nested subsystems [12, 16]. The calculation of the Lyapunov function is then performed recursively from inside of the loop. The objective of this technique is to calculate, at each stage of the process, a virtual control is thus generated to ensure the convergence of the system towards its equilibrium state [7, 12]. This can be achieved from the functions of Lyapunov which ensure step by step the stabilization of each synthesis step. Unlike most other methods, backstepping has no nonlinearity constraints.

The model of the double stator induction machine which has been presented is used later for the synthesis of the control law, where the factors μ_1, μ_2 given by:

$$\mu_1=\frac{L_m}{L_m+L_r},\quad \mu_2=\frac{R_r}{L_m+L_r};$$

$$\begin{cases}\dfrac{\mathrm{d}i_{ds1}}{\mathrm{d}t}=\dfrac{1}{L_{s1}}\left[V_{ds1}-R_{s1}i_{ds1}+\omega_s^*\left(L_{s1}i_{qs1}+T_r\Phi_r^*\omega_{sr}^*\right)\right];\\ \dfrac{\mathrm{d}i_{ds2}}{\mathrm{d}t}=\dfrac{1}{L_{s2}}\left[V_{ds2}-R_{s2}i_{ds2}+\omega_s^*\left(L_{s2}i_{qs2}+T_r\Phi_r^*\omega_{sr}^*\right)\right];\\ \dfrac{\mathrm{d}i_{qs1}}{\mathrm{d}t}=\dfrac{1}{L_{s1}}\left[V_{qs1}-R_{s1}i_{qs1}-\omega_s^*\left(L_{s1}i_{ds1}+\Phi_r^*\right)\right];\\ \dfrac{\mathrm{d}i_{qs2}}{\mathrm{d}t}=\dfrac{1}{L_{s2}}\left[V_{qs2}-R_{s2}i_{qs2}-\omega_s^*\left(L_{s2}i_{ds2}+\Phi_r^*\right)\right];\\ \dfrac{\mathrm{d}\Omega}{\mathrm{d}t}=\dfrac{1}{J}\left[P\mu_1\left(i_{qs1}+i_{qs2}\right)\Phi_r^*-B_\omega\Omega-T_L\right];\\ \dfrac{\mathrm{d}\phi_r}{\mathrm{d}t}=-\mu_2\Phi_r+R_r\mu_1\left(i_{ds1}+i_{ds2}\right).\end{cases}\qquad(18)$$

First step «flux loop». To ensure the operation of the machine in the linear regime (out of saturation), a flux control is also carried out such that Φ_r follows an imposed trajectory Φ^*_r. To achieve this goal we pose:

$$e_1=\Phi_r^*-\Phi_r.\qquad(19)$$

By derivation, we obtain $\dot{e}_1=\dot{\Phi}_r^*-\dot{\Phi}_r$. The first Lyapunov candidate function is defined by:

$$V_1=\frac{1}{2}e_1^2.\qquad(20)$$

By derivation, we obtain:

$$\dot{V}_1=e_1\dot{e}_1;\qquad \dot{V}_1=e_1\left[\dot{\Phi}_r^*+\mu_2\Phi_r-R_r\mu_1\left(i_{ds1}+i_{ds2}\right)\right],$$

and according to Lyapunov stability, the origin $e_1 = 0$ of system (20) is asymptotically stable when $\dot{V}_1$ is defined as negative.

We then define (i_{ds1} + i_{ds2}) as the virtual control. Indeed, for an expert in the field of electrical machines, this choice of virtual control is normal, that is to say, one looks for the value that the virtual control must take origin as stable, so the stabilizing virtual function is determined by: $\dot{V}_1=-k_1e_1^2<0$ with $k_1 > 0$. We find:

$$i_{ds1}^*+i_{ds2}^*=\frac{1}{\mu_2L_m}\left[\mu_2\hat{\phi}_r+\dot{\phi}_r^*+k_1e_1\right]\qquad(21)$$

with $i_{ds1}^*=i_{ds2}^*$, represents the references of the components of the current.

Second step «currents loop». For this step, our goal is to eliminate the current regulators, by calculation of the control voltages. Other errors concerning the components of the stator current and their references are defined:

$$\begin{cases}e_2=i_{qs1}^*-i_{qs1};\\ e_3=i_{ds1}^*-i_{ds1};\\ e_4=i_{qs2}^*-i_{qs2};\\ e_5=i_{ds2}^*-i_{ds2}.\end{cases}\qquad(22)$$

The dynamics of errors is given by:

$$\begin{cases} \dot{e}_2 = \dfrac{\mathrm{d}i_{qs1}^*}{\mathrm{d}t} - \dfrac{1}{L_{s1}}\left(V_{qs1} + \delta_1\right); \\ \dot{e}_3 = \dfrac{\mathrm{d}i_{ds1}^*}{\mathrm{d}t} - \dfrac{1}{L_{s1}}\left(V_{ds1} + \delta_2\right); \\ \dot{e}_4 = \dfrac{\mathrm{d}i_{qs2}^*}{\mathrm{d}t} - \dfrac{1}{L_{s2}}\left(V_{qs2} + \delta_3\right); \\ \dot{e}_5 = \dfrac{\mathrm{d}i_{ds2}^*}{\mathrm{d}t} - \dfrac{1}{L_{s2}}\left(V_{ds2} + \delta_4\right), \end{cases} \quad (23)$$

with:

$$\begin{cases} \delta_1 = -R_{s1}i_{qs1} - \omega_s^*\left(L_{s1}i_{ds1} + \Phi_r^*\right); \\ \delta_2 = -R_{s1}i_{ds1} + \omega_s^*\left(L_{s1}i_{ds1} + T_r\Phi_r^*\omega_{sr}^*\right); \\ \delta_3 = -R_{s2}i_{qs2} - \omega_s^*\left(L_{s2}i_{ds2} + \Phi_r^*\right); \\ \delta_4 = -R_{s2}i_{qs2} + \omega_s^*\left(L_{s2}i_{ds2} + \Phi_r^*\right). \end{cases} \quad (24)$$

The new function of Lyapunov is given by:

$$V_2 = \frac{1}{2}\left(V_1 + e_2^2 + e_3^2 + e_4^2 + e_5^2\right). \quad (25)$$

By derivation, we obtain:

$$\dot{V}_2 = \dot{V}_1 + e_3\dot{e}_3 + e_4\dot{e}_4 + e_5\dot{e}_5 + e_2\dot{e}_2 .$$

We look for the value that must be taken by the reference command [$V_{ds1}^*, V_{qs1}^*, V_{ds2}^*, V_{qs2}^*$] for the origin is stable. So the stabilizing virtual function is determined so that:

$$\dot{V}_2 = \dot{V}_1 - k_3e_3^2 - k_4e_4^2 - k_5e_5^2 - k_2e_2^2 < 0 .$$

The stability of the control is obtained if and only if a good choice of gains: k_1, k_2, k_3, k_4, k_5 is made. And k_2, k_3, k_4, k_5 positives gains. For this one poses:

$$\begin{cases} V_{qs1}^* = L_{s1}\left(k_2e_2 - \delta_1 + \dfrac{\mathrm{d}i_{qs1}^*}{\mathrm{d}t}\right); \\ V_{ds1}^* = L_{s1}\left(k_3e_3 - \delta_2 + \dfrac{\mathrm{d}i_{ds1}^*}{\mathrm{d}t}\right); \\ V_{qs2}^* = L_{s2}\left(k_4e_4 - \delta_3 + \dfrac{\mathrm{d}i_{qs2}^*}{\mathrm{d}t}\right); \\ V_{ds2}^* = L_{s2}\left(k_5e_5 - \delta_4 + \dfrac{\mathrm{d}i_{ds2}^*}{\mathrm{d}t}\right). \end{cases} \quad (26)$$

Proposed Kalman filter for speed, flux, and load torque sensorless control. The extended Kalman filter (EKF) is a mathematical tool capable of determining state values, immeasurable or parameters of the state system from measurable physical values. It allows estimating the state of a nonlinear system. This filter is based on a number of assumptions, including noise. Indeed, that supposes that the noises which affect the model are centered and white and that these are decor related from the estimated states. In addition, state noise must be decor related from measurement noise [8, 17].

The algorithm of the EKF is the same as that of the standard Kalman filter which has two steps:

- a prediction step which consists in evaluating the state variables from the system model;
- correction step which consists in correcting the prediction error on the variables using the existing differences between the observed and measured variables.

These two steps are preceded by an initialization of the state vector and of the covariance matrices [8]. This filter formulated by the following equations:

$$X(k+1) = f\left(X(k), U(k)\right) + \psi(k) = = A_d X(k) + B_d U(k) + \psi(k); \quad (27)$$

$$Y(k) = \hbar\left(X(k)\right) + \Gamma(k) = C_d X(k) + \Gamma(k). \quad (28)$$

The discrete extended noises ($\psi(k)$ and $\Gamma(k)$) are white, Gaussian and of zero mean, and the covariance matrices ($Q(k)$, $R(k)$) are defined positive and symmetrical.

Equation of the Kalman observers. The extended Kalman observer is generally defined by the following equations [8, 17]:

- Estimate of the initial state: $\hat{X}(0)$;
- Variance the initial state $P(0)$ with:

$$P(k) = A_d P(k-1) A_d^T + Q ; \quad (29)$$

- Kalman gain:

$$G(k) = P(k) C_d^T \left[C_d P(k-1) C_d^T + R\right]^{-1} ; \quad (30)$$

- State estimates $\hat{X}(k)$ by (update):

$$\hat{X}(k+1) = \hat{X}(k) + G(k)\left[y(k) - C_d \hat{X}(k-1)\right]; \quad (31)$$

- Updating the covariance matrix P:

$$P(k+1) = (I - G) C_d P^{-1}(k). \quad (32)$$

Application of the Kalman filter to DSIM. The application of the EKF is based on the reduced system model. The ideal case consists in choosing a reduced model of the DSIM established in the reference frame *d-q* linked to the rotor.

In this case, the EKF is applied to a system whose estimated state vector is extended to the mechanical speed of rotation $\hat{\omega}(k)$, the flux of the rotor $\hat{\phi}_r(k)$ and to the load torque $\hat{T}_L(k)$.

If it clears that the estimation the constant resistance torque T_L, we assume that it changes slowly, so we can use for the load torque the following model [15]:

$$\frac{\mathrm{d}T_L}{\mathrm{d}t} \cong 0 . \quad (33)$$

So, we choose the extended state model of the system is described by:

$$\begin{cases} \dot{X} = AX + BU; \\ y = CX, \end{cases} \quad (34)$$

with:

$$X = \left[\vartheta \quad \omega \quad \phi_r \quad T_L\right]^T ;$$

$$U = \left[i_{ds1} \quad i_{ds2} \quad i_{qs1} \quad i_{qs2}\right]^T ;$$

$$C = \left[1 \quad 0 \quad 0 \quad 0\right];$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{B_\omega}{J} & 0 & -\dfrac{1}{J} \\ 0 & 0 & -\mu_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix};$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\mu_1 \phi_r^*}{J} & \frac{\mu_1 \phi_r^*}{J} \\ \mu_1 L_m & \mu_1 L_m & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

The discrete system which determines the behavior of the continuous filter at discrete times is necessary for the implementation of the Kalman filter in real time.

Considering the process noise and the measurement noise $\psi(k)$, and $\Gamma(k)$ assume the sampling time T_c. The discrete model for (34) is expressed by:

$$\begin{cases} X(k+1) = A_d X(k) + B_d U(k) + \psi(k); \\ y(k) = C_d X(k) + \Gamma(k); \end{cases} \tag{35}$$

with

$$A_d = \begin{bmatrix} 0 & T_c & 0 & 0 \\ 0 & 1 - T_c \frac{B_\omega}{J} & 0 & -\frac{T_c}{J} \\ 0 & 0 & 1 - \mu_2 T_c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix};$$

$$B_d = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & T_c \frac{\mu_1 \phi_r^*}{J} & T_c \frac{\mu_1 \phi_r^*}{J} \\ T_c \mu_1 L_m & T_c \mu_1 L_m & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix};$$

$$C_d = [1 \quad 0 \quad 0 \quad 0].$$

Finally, the critical step in the EKF is the search for the best covariance matrices Q and R to be established based on the stochastic properties of the corresponding noise are chosen by simulation tests to achieve a desired evaluation performance.

Simulation results. In order to validate the control strategies as discussed, associate the parts of the article and achieve a numerical simulation using the system described in Fig. 3.

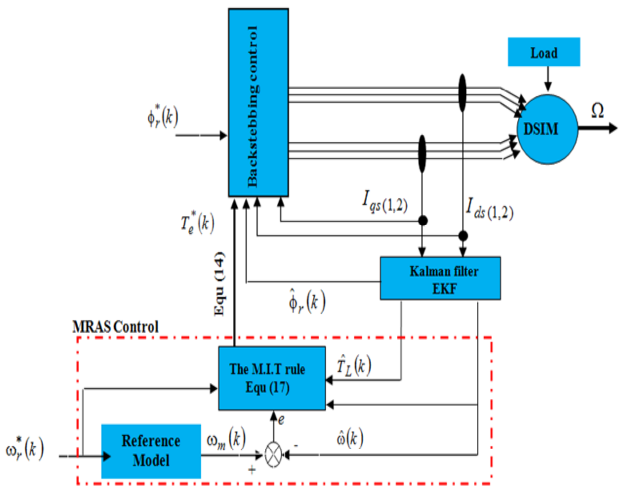

Fig. 3. Presentation of model reference adaptive backstepping control of DSIM motor combining with EKF

The verification and testing of the proposed command is synthesized for the induction double stator machine, and combined with the Kalman observer using simulation series by MATLAB. By the following points:

1. The machine parameters (DSIM) used in simulation is given in Table 1, the reference model chosen by: $a_m = b_m = 30$ (faster than the system).

Table 1

The used DSIM parameters [1, 12]

Parameter name	Symbol	Value	Unit
DSIM mechanical power	P_n	4.5	kW
Nominal voltage	V_n	220	V
Nominal current	I_n	5.6	A
Nominal speed	N	2970	rpm
Stator resistances	$R_{s1} = R_{s2} = R_s$	3.72	Ω
Rotor resistance	R_r	3.72	Ω
Stator self inductances	$L_{s1} = L_{s2} = L_s$	22	mH
Rotor self inductance	L_r	6	mH
Mutual inductance	L_m	0.3672	H
Moment of inertia	J	0.0662	kg·m^2
Viscous friction coefficient	B_ω	0.001	N·m/rad
Supply frequency	f	50	Hz
Pole pairs number	p	1	

2. The gains which guarantee backstepping stability are chosen by: $K_1 = 300$, $K_2 = 500$, $K_3 = 500$, $K_4 = 500$, $K_5 = 500$ and for the stability of Lyapunov $\gamma = 0.01$.

3. The Kalman filter parameters are set by: $P(0) = 0.2 \cdot I_4$, $Q = 0.7 \cdot I_4$, $R = 0.1$.

4. The estimated quantities ($\hat{\omega}_r$, $\hat{\phi}_r$, $\hat{T}_L$) can be used in the control law instead of real quantities (ω_r, ϕ_r, T_L) without posing a problem of stability. We place a white measurement noise (concerning the sensors) at the level of the quantities (ω_r, ϕ_r, T_L) or practically the noise is chosen according to the category of quantity measured, and note that in the worst cases the sensors are all assigned to the same time, in this case the EKF filters the maximum noise to maintain the nominal quantities of DSIM (avoid system malfunction).

5. Based on the error ($e = \omega_r - \omega_m$), and the estimated speed by adjusting the actual values of θ_1 and θ_2 online by (17) with their initial values θ_1^0, θ_2^0, which are given by (15). The law of M.I.T is used to calculate the command T_e^* by (14).

6. The objective of the speed control is to bring its value to 300 rad/s and maintain this value. In addition, the desired flux is fixed at 1 Wb. A positive resistance torque of 15 N·m is applied between 1.5 s and 2.5 s. The results presented as follows.

Figures 4–7 present the M.I.T regulator parameters (θ_1, θ_2), the rotor speed, rotor flux and the resistive torque.

The regulator parameters (θ_1, θ_2) have been improved (adapted) in order to check the condition that the error is equal to zero (Fig. 4).

We note that all the estimated quantities follow the evolution of these real values (speed, flux, load torque) of the DSIM well, so the estimation is done in a satisfactory manner (Fig. 5, 6). The speed follows its reference value (ω_m), and after the application of the load torque $C_r = 15$ N·m at $t = 1.5$ s, the electromagnetic torque takes the estimated load torque value (Fig. 7). The second consists in reversing the speed of rotation from 100 to –100 rad/s at time $t = 1$ s under load torque $C_r = 15$ N·m since $t = 1.5$ s.

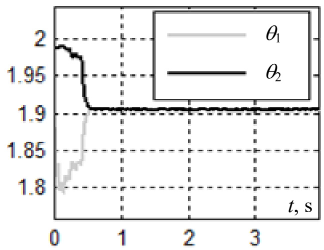

Fig. 4. The adjustment of parameters (θ_1, θ_2) of the controller

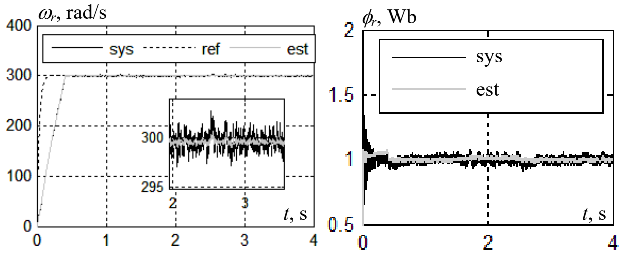

Fig. 5. Estimated and reference speed, rotor flux of the DSIM motor using Kalman filter

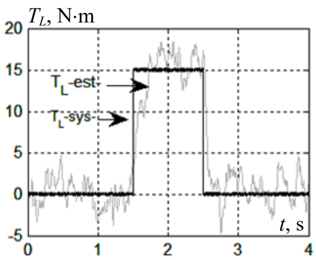

Fig. 6. Estimated and reference of the load torque by Kalman filter

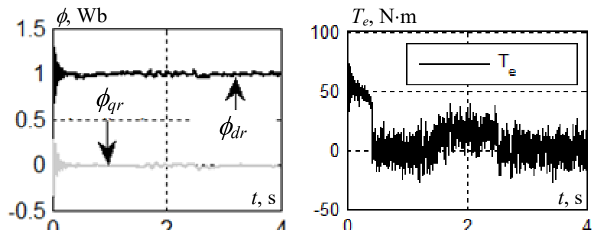

Fig. 7. Evolution of electromagnetic torque and the rotor flux components (ϕ_{dr}, ϕ_{qr}) of the DSIM

In Fig. 8 the regulator parameters (θ_1, θ_2) have been evolved (adapted) in a form which must check the condition of the error equal to zero and their stabilities are tied by speed stability ($\Im(0) = 0$).

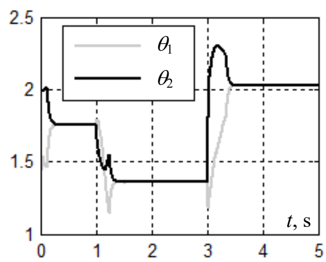

Fig. 8. The adjustment of parameters (θ_1, θ_2) of the controller during speed variation test under load

The speed follows its reference and reverses after (0.25 s) (Fig. 9) leads to a negative torque (-50 N·m) during the interval of the speed inversion, then it oscillates author zero when the speed reaches -100 rad/s (Fig. 10).

The estimated rotor flux follows its set point with a slight disturbance during the time of the speed reversal (Fig. 9). The speed reversal generates an increase in the stator current i_{as1}, but the latter retains its sinusoidal shape (Fig. 11).

The electromagnetic torque (Fig. 10) admits a significant peak at startup and also the components of the current i_{qs1} and finally the shape of the components of the rotor flux show that the decoupling is always maintained (Fig. 11).

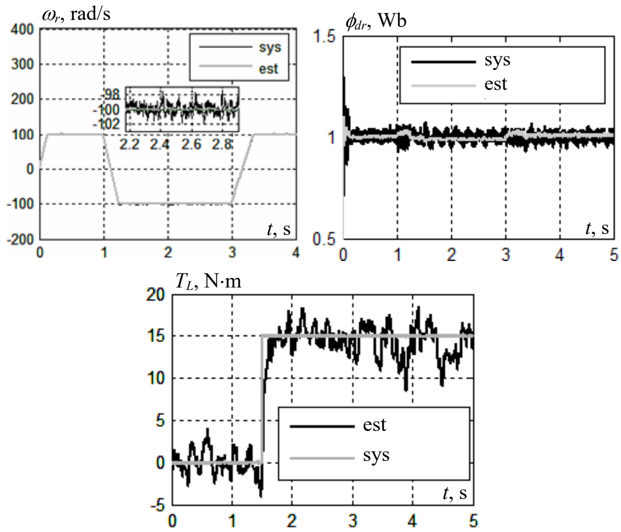

Fig. 9. Estimated and reference of speed, rotor flux, of the DSIM using Kalman filter during speed variation test under load

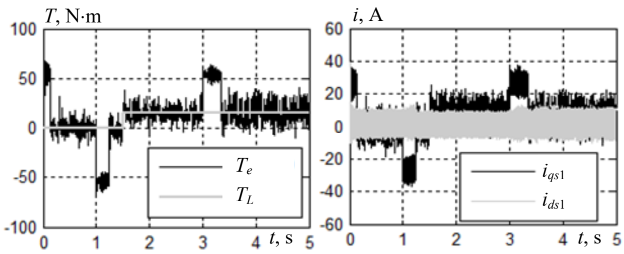

Fig. 10. Evolution of electromagnetic torque and currents i_{ds1}, i_{qs1} during speed variation test under load

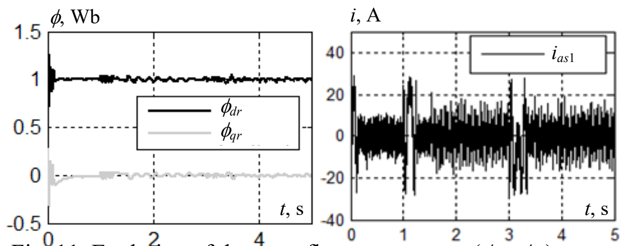

Fig. 11. Evolution of the rotor flux components (ϕ_{dr}, ϕ_{qr}) stator current i_{as1} during speed variation test under load

Robustness tests. Figures 12–14 show the performance of DSIM regulation with respect to the increase in the moment of inertia by 100 % of its nominal value. The regulator parameters (θ_1, θ_2) have been evolved (adapted) in a form which must verify the condition of the error equal to zero (Fig. 12), the estimated quantities follow the evolution of these real values well (Fig. 13), this increase does not affect the values of electromagnetic torque, and stator current (Fig. 13).

The second test contains the dynamic response of the controller during robustness tests to the increase in the rotor resistance by 100 % of its nominal value with varied load. In Fig. 15 the regulator parameters (θ_1, θ_2) have been changed (adapted) always in the sense that the estimation error is equal to zero.

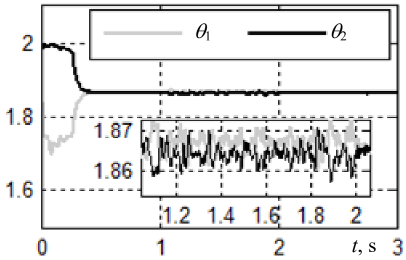

Fig. 12. Dynamic response of parameters (θ_1, θ_2) of the controller during robustness tests with respect to total inertia J

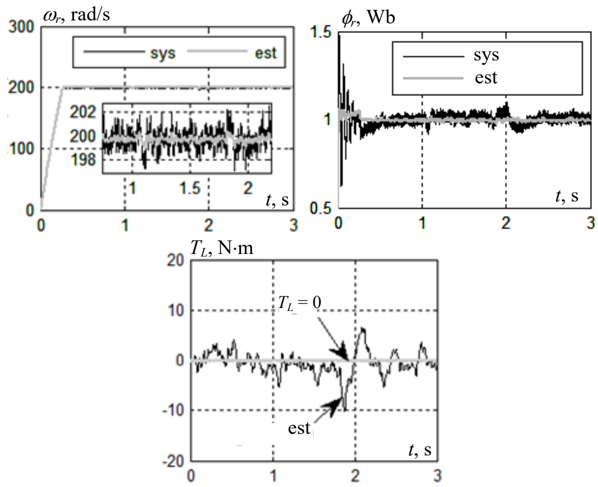

Fig. 13. Estimated speed, rotor flux and load torque

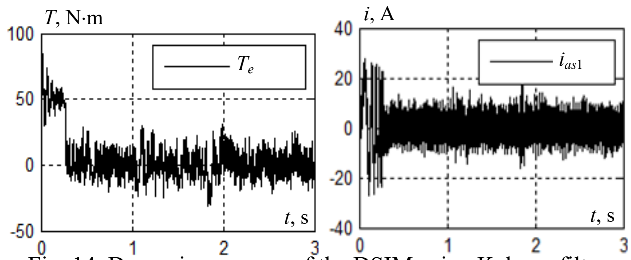

Fig. 14. Dynamic response of the DSIM using Kalman filter during robustness tests with respect to total inertia J

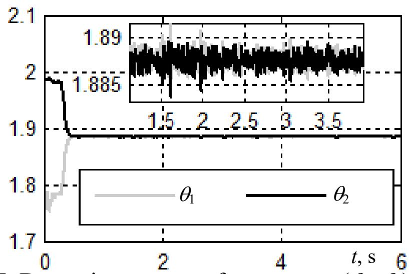

Fig. 15. Dynamic response of parameters (θ_1, θ_2) of the controller during robustness tests with $R_r = 2{\cdot}R_{rn}$ from $t = 1$; 2 s with varied load

From Fig. 16 we see that the quantities estimated by Kalman filter follow their real values obtained despite the variation of the rotor resistance. It is clearly noted that no influence appears during the variation of the rotor resistance in no-load operation [5; 6] s and operating under load $t > 1$ s. The electromagnetic torque compensates for the load torque even when applying a load greater than the nominal load torque $C_r = 21$ N·m (Fig. 17).

A large current draw i_{as1} appears during the application of the load where the rotor resistance $R_r = 2{\cdot}R_{rn}$. The components of the rotor flux follow their imposed values in Fig. 18.

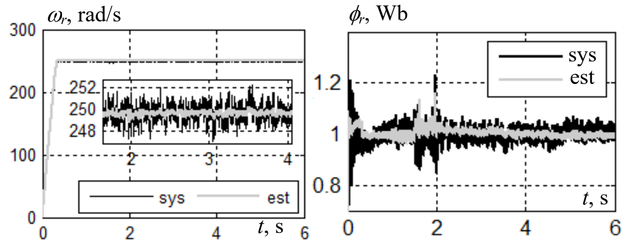

Fig. 16. Estimated speed and rotor flux

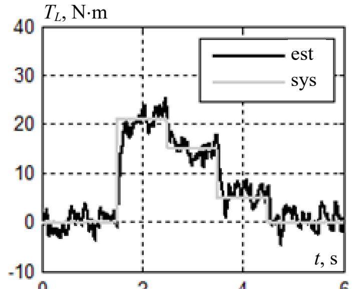

Fig. 17. Load torque

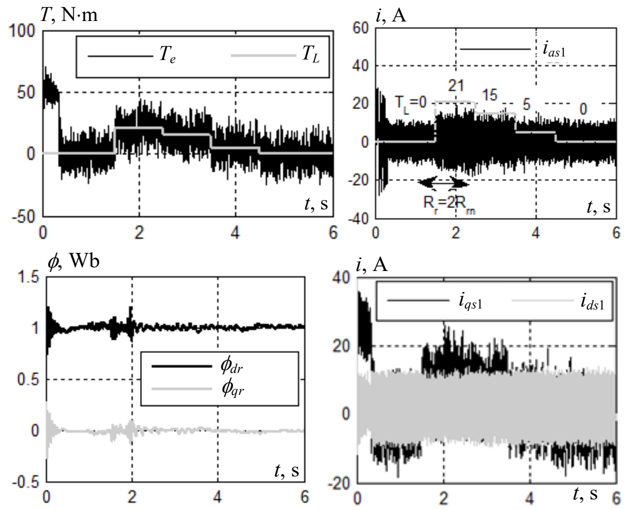

Fig. 18. Dynamic response of the DSIM using Kalman filter during robustness tests with $R_r = 2{\cdot}R_{rn}$ from $t = 1$; 2 s with varied load

Conclusions.

1. This study proposes a robust model reference adaptive backstepping control law for the speed regulation of double stator induction motor drive system demonstrating lumped uncertainty with Extended Kalman filter observer (speed, flux and load torque). First, the system mathematical model for the field oriented control is introduced. Then, based to the Lyapunov stability as a common point, the robust controller has hybrid by two loops.
2. The analyzed of the speed loop by the adaptive rule where the regulator parameters adjustment has been online and the current loops by backstepping control with load disturbance rejection into account.
3. It can clearly be seen that the development of the proposed robust control law has been applied. To avoid the problem of the persecutory effects of speed sensors and the resistant torque, a developed Kalman observer has been proposed.
4. The results obtained in simulation are very close to those obtained using a speed sensor. Finally, as a perspective, it would be interesting to add an estimator for the rotor resistance and the experimental implementation

of the proposed control scheme will be addressed in the future work.

Conflict of interest. The authors declare that they have no conflicts of interest.

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