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Presenting a New Adaptive Control Method Based on I&I Technique for IM Systems with Uncertain Dynamic

Hamid Khorasani
Gonabad Faculty of Electrical and Electronics, Department of Electrical Engineering Faculty of Khorasan, Gonabad Branch, Technical and Vocational University (TVU), Tehran, Iran

Abstract:
Since, majority of systems are non-linear with uncertain parameters, to describe mathematical model, adaptive methods are suggested for online data collection and automatic adjustment of control parameters as parameters of system are not determined or dynamics of system are highly complicated. In this paper, widely used non-linear system of induction motor has been examined and a new and efficient adaptive controller that is distinguished from previous methods has been introduced for system based on Immersion and Invariance (I&I) method. To design controller, induction motor system has been considered in error mode and the considered errors in system have led to motor's uncertain dynamic making it difficult to control induction motor. Accordingly, controller has been designed adaptively and the named parameters- that may be changed under working conditions of motor during time- are estimated online. Adaptive rules are obtained from stability analysis based of I&I method. According to the results obtained from simulation in MATLAB, it will be possible to see effectiveness of controller obviously that is able to track optimal path also to generate suitable control signals in presence of unknown parameters in system model.

Keywords: *Adaptive control method, I&I technique, IM systems, uncertain dynamic*

1. Introduction

Control of induction motors (IM) is an attractive subject for study due to nonlinearity, unmodeled dynamics, and variations and uncertain in parameters and external disturbances. The main advantages of IM are that it do not need to an electrical connection between the stationary and the rotating parts [1,2]. Indeed, IM don't need any mechanical commutator, because they are free motors. Moreover, induction motors also have low weight and inaction, high proficiency and a high excess capability [3]. Also IM are inexpensive and more robust, and less proves to any disaster at high speeds [4]. Moreover, the IM can run in explosive conditions due to there are no sparks [5]. Regarding to all advantages mentioned above, the IM must be considered as the perfect electrical to mechanical energy converter. Thus the IM is considered to be the work horse of production [6].

The IM is characterized by a simple mechanical construction, better efficiency, low costs and robust model [7]. The induction motor (IM) has been considered as a multi-variable, strong coupling, and nonlinear system, so the control of IMs is a challenging problem. Practically the design of motor control laws is required to remark more entangle faulty case which may cause to induce system instability and even catastrophic effects while there are many results about induction motors. Owing to multivariable and nonlinearities the high-performance control of IMs has dealt with a great attraction until now. To guarantee good performances and stability of the IM in presence of parameters variations, it is necessary to use more elaborate control strategies [8]. IM admits a strongly nonlinear dynamic model. It constitutes an important research field for the synthesis of advanced control.

In general, it can be said that the design of these controllers requires an accurate mathematical model of the system and requires the exact amount of its parameters; otherwise, the stability of the function system is subjected to the parametric variations, and also the mathematical complexity of the calculations. To solve these issues, different control laws have been generally justified by utilizing robustness methodology and dynamical performances of IMs [10, 11], such as Sliding-Mode Control (SMC), Fuzzy Logic (FLC) [7, 9, 12, 13, 14], Neural Network Control(NNC) [7, 9, 15-17], Optimal Control (OC) [18, 19], Adaptive Control[20].

The I&I is a new method to design a robust controller in systems with uncertainties [21, 22]. The problem of planning globally stabilizing control laws for general nonlinear systems has been directed effectually due to recent conceptual prospect of I&I method. The principle notion in this method is to remodel the stabilization in terms of system immersion. To attain the control objective through immersing the system dynamics toward a targeted system lead to capture desired behavior [21]. Indeed, this recent method is used in most of numerous modern engineering systems. As it is indicated, in the presence of uncertainties and faults the suggested method is robust and also it yields considerable proficiency.

In accordance with many researches, various applications for I&I principle have been also offered. In [23] two controllers based on I&I and SMC control has been compared. Given the implicit resemblance between the SMC and the I&I principle, the comparison allows us to highlight the advantages and disadvantages of each control strategy for robust lane keeping for intelligent vehicles. To validate the control strategies, the closed-loop system has been simulated on Matlab-Simulink has been made using the experimental data acquired on the vehicle DYNA of Heudiasyc laboratory, a Peugeot 308, according to several real driving scenarios. The validation shows robustness and performances of each control approach, and puts in evidence the improvement brought by I&I controller.

Since I&I are used as a new method for designing nonlinear and adaptive controllers, it is based on system immersion and manifold invariance. I&I approach used to obtain the control objective by immersing the plant dynamics in a possibly lower-order target system that reaches to the desired behavior [24, 25].

The most significant advantage and difference of I&I method compared to sliding-mode method and presented method for induction motor is its generalization. Moreover, it is possible to have a better report and description of system model. Control rules in design avoid using a discontinuous element or term that leads to chattering phenomenon in sliding-mode controller. In addition, simplicity and robust against parameter variations and disturbances as well as generating rapid control signals can be mentioned as advantages of this technique. To investigate the history and new mode of the controller in modern, important and practical systems, some studies performed about I&I method are reviewed herein.

Using the concept of I&I design methodology, the proposed nonlinear controller is used to not only achieve power angle stability, frequency and voltage regulation but also ensure that the closed-loop system is transiently and asymptotically stable [26].

Even if an I&I observer formulation could be devised, a simpler, more agile and robust, nonlinear sliding mode estimation of the required system state will be preferred for a practical implementation of a full state I&I controller [27].
Recently, I&I design technique was proposed for the design of a nonlinear coordinated generator excitation and SVC controller for transient stability enhancement and voltage regulation of power systems. From our previous work, the nonlinear I&I controller highly relies upon selecting a target dynamical system capturing the desired behavior of the closed-loop system to be controlled [28].

In [29] a novel I&I -based adaptive controller for nonlinear under-actuated quadrotor systems subject to uncertain inertial parameters. The solution to the trajectory tracking problem is transformed to stabilizing its corresponding error system asymptotically. To avoid singularity in the command attitude extraction, a saturated backstepping control strategy with smooth hyperbolic tangent functions is developed to synthesize a command force in the position loop, where an I&I adaptive methodology is introduced to update the mass estimation. The I&I adaption guarantees the asymptotic convergence of the mass estimation to its actual value.

The advanced I&I control method, in particular, was applied to the design of a nonlinear coordinated generator excitation and SMES controller for transient stability enhancement of power systems [30].
Moreover, Kanchanaharuthai proposed an adaptive nonlinear I&I controller for transient stability enhancement and voltage regulation of power systems with SMES, even if there are some unknown parameters in the system. The adaptive I&I control technique can guarantee the overall closed-loop dynamics and the great achievement of the desired dynamic performances but its design procedure was rather complicated [31].

Although the I&I control methodology is the most effective and can be applied for various types of systems, it has main disadvantages. In particular, this method has no systematic ways in selecting the mapping from an algebraic equation, an appropriate target dynamics, and a suitable Lyapunov (energy) function, respectively [32].
I&I control method different from the classical adaptive method; it is essentially a non–CE-based adaptive control technique that overcomes the performance limitations arising from CE-based designs. It allows for prescribed uniformly stable dynamics to be assigned to the parameter estimation error, thus leading to a modular control scheme that is much easier to tune than the one obtained from the classical adaptive approach. That is why this approach is favored by many researchers and numerous research results are emerging in recent years [33].

The use of the non-linear sliding mode method provides best performances for motor operation and robustness of the control law in compared I&I technique with external and internal perturbations [34].

A study focused on using a novel fast terminal sliding mode control approach based on system immersion and manifold invariant (FTSMC-I&I). I&I method is applied to design an adaptive disturbance estimator in order to improve estimation accuracy and convergence speed with respect to parametric uncertainties and disturbances that are encountered in sailing applications. As a result, the estimation error of disturbances tends to zero and its dynamic process can be adjusted. It is shown that the proposed method can guarantee the asymptotical stability and the finite time convergence of the system from Lyapunov stability analysis. Compared with the backstepping adaptive sliding mode control, the proposed control method can achieve higher precision and better robustness in the presence of practical input limits [35].

In [36], a new adaptive sliding mode control is proposed to control nonlinear systems with parametric uncertainties and matched and unmatched external disturbances. The proposed method first combines immersion and invariance (I&I) adaptive scheme with sliding mode control (SMC), which preserves the advantages of the two methods. The proposed method is different from the approach of combining the backstepping adaptive scheme and sliding mode control in the parameter estimation law, which allows for prescribed dynamics to be assigned to the estimation error and is easier to tune. Finally, the method is applied to control a class of power systems, and simulation results show the advantages of the proposed method.

The main contribution of this study is to present a new adaptive control method based on I&I technique for a class of IM systemswith uncertain dynamic. This controller guarantees the track of rotor magnetic flux and speed reference values in a best way. To design the controller, IM has been examined in the fault mode. Rotor resistance variation due to motor warming and changes in load torque that occurs suddenly considered as uncertain parameters in the IM system. Accordingly, controller has been designed adaptively and the uncertainties include time variable parameters in IM system are estimated online. Adaptive rules will be obtained from stability based on I & I technique. Simulations results obviously display that the offered controller can control the system with high performance.

As development of industrial systems controlling is closely related to development in control strategies and technologies, this study was conducted to find a suitable control method in order to solve problems in induction motors. This paper has been organized as follows: second section after introduction part presents the model of induction motor with its details and definition of control problem. Third part includes design of adaptive controller based on the I&I method. The next part explains simulation results. Conclusion is the last part of this paper.

2. Mathematical model of induction motor and definition of control problem

2.1. Description of Mathematical Model of Induction Motor

The mathematical model of induction motor in space of synchronously rotating two-phase reference frame (d-q) has been described at this part [33,34]. As it is seen, the model of induction motor in non-linear. Figure 1 shows a vector diagram of induction motor

$$\begin{cases} \dfrac{d\omega}{dt} = \mu(\phi_{rd} i_{sq} - \phi_{rq} i_{sd}) - \dfrac{n_p T_r}{J} \\ \dfrac{d\phi_{rd}}{dt} = -\dfrac{1}{\tau_r}\phi_{rd} + (\omega_s - \omega)\phi_{rq} + \dfrac{M_{sr}}{\tau_r} i_{sd} \\ \dfrac{d\phi_{rq}}{dt} = -\dfrac{1}{\tau_r}\phi_{rq} - (\omega_s - \omega)\phi_{rd} + \dfrac{M_{sr}}{\tau_r} i_{sq} \\ \dfrac{di_{sd}}{dt} = \dfrac{\beta}{\tau_r}\phi_{rd} + \beta\omega\phi_{rq} - \dfrac{1}{\tau_1} i_{sd} + \omega_s i_{sq} + \dfrac{1}{L_1} V_{sd} \\ \dfrac{di_{sq}}{dt} = \dfrac{\beta}{\tau_r}\phi_{rq} - \beta\omega\phi_{rd} - \dfrac{1}{\tau_1} i_{sq} - \omega_s i_{sd} + \dfrac{1}{L_1} V_{sq} \end{cases} \quad (1)$$

where

(V_{sd}, V_{sq}) the components of the stator voltage vector

(ϕ_{rd}, ϕ_{rq}) the components of the rotor flux

(i_{sd}, i_{sq}) the components of the stator current vector

Ω the rotor speed

ω_s the stator electric angular frequency

T_r the unknown load torque

Mechanical and electrical parameters of model are:

$$\tau_r = \frac{L_r}{R_r}; L_1 = L_s - \frac{{M_{sr}}^2}{L_r}; R_1 = R_s + R_r\left(\frac{M_{sr}}{L_r}\right)^2;$$
$$\beta = \frac{M_{sr}}{L_r L_1}; \mu = n^2{}_p\left(\frac{M_{sr}}{J L_r}\right); \tau_1 = \frac{L_1}{R_1} \quad (2)$$

Where

stator/rotor inductances L_s, L_r

R_s, R_r the stator/rotor resistance

M_{sr} the mutual inductance

n_p the number of pole pairs

J the moment of inertia

It should be noted that this study has ignored the friction in mechanical system equations.

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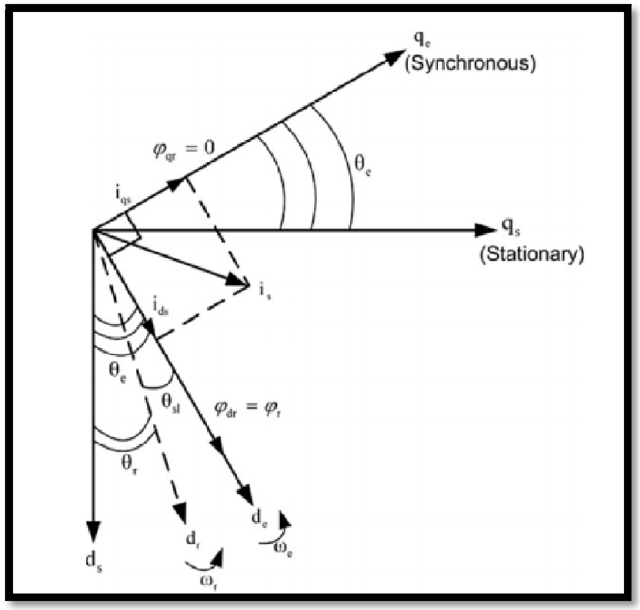

Figure 1: Vector Diagram of Induction Motor

2.2. Induction Motor Model with Uncertain Dynamic

`To simplify calculations, the system is rewrite in state-space form in which, x_1 and x_2 indicate rotor speed ω and magnetic flux (ϕ_{rd}, ϕ_{rq}), u_1 and u_2 are control inputs, x3 and x4 indicate stator current vectors (i_{sd}, i_{sq}). As the study is performed on IM with uncertain dynamic, θ_1 and θ_2 are considered as uncertainties in the IM system.

$$\begin{aligned}
\dot{x}_1 &= \left[\mu x_2 x_4 - a_1\right] + b_1\theta_1 \\
\dot{x}_2 &= \left[-a_2 x_2 + a_3 x_3\right] + \left[b_2 x_2 + b_3 x_3\right]\theta_2 \\
\dot{x}_3 &= \left[a_4 x_2 - a_5 x_3 + x_1 x_4 + a_6 x_4^2 / x_2\right] + \left[b_4 x_2 + b_5 x_3 + b_6 x_4^2 / x_2\right]\theta_2 + \frac{1}{L_1}u_1 \\
\dot{x}_4 &= \left[-\beta x_1 x_2 - a_5 x_4 - x_1 x_3 + a_6 x_3 x_4 / x_2\right] + \left[b_5 x_4 + b_6 x_3 x_4 / x_2\right]\theta_2 + \frac{1}{L_1}u_2
\end{aligned}$$

(3)

The parameters a_1, a_2, a_3, a_4, a_5, a_6 andb_1, b_2, b_3, b_4, b_5, b_6 are given by

$$\begin{aligned}
&a_1 = \frac{n_p T_{rN}}{J},\ b_1 = -\frac{n_p}{J}, a_2 = \frac{1}{\tau_{rN}},\ a_3 = \frac{M_{sr}}{\tau_{rN}}, b_2 = -\frac{1}{L_r}, b_3 = \frac{M_{sr}}{\tau_{rN}} \\
&a_4 = \frac{\beta}{\tau_{rN}}, a_5 = \frac{1}{\tau_{1N}}, a_6 = \frac{M_{sr}}{\tau_{rN}}, b_4 = \frac{\beta}{l_r}, b_5 = -\frac{M_{sr}^2}{L_1 L_r^2}, b_6 = -\frac{M_{sr}}{L_r}
\end{aligned}$$

(4)

The following hypotheses have been considered in induction motor model:

- Hypothesis 1: induction motor model has fault and two faults are considered in induction motor model. The first fault include changes in rotor resistance that may be changed 100% during operation because of warming and skin effect and second fault consists of changes in load torque that is an uncertain parameter basically[33, 34].
- Hypothesis 2: load torque and rotor resistance are unknown. These parameters are considered in induction motor model leading to dynamic uncertainty showed as $\theta_2 = R_r - R_{rN}$ and $\theta_1 = T_r - T_{rN}$ parameters in induction motor equations.
- Hypothesis 3: The equation of rotor resistance variation is obtained from equation $R_r = R_{rN} + R_{rN}\left(1 - \exp\left(-1.2t\right)\right)$ [33, 34].

3. Adaptive Immersion and Invariance Control Design and Application to an IM

Since the studied system in this research is in fault mode and the induction motor considered with uncertain dynamic, the main objective of this part is to design a suitable adaptive controller in order to estimate time variable parameters in the IM system. Adaptive rules are reached from stability analysis based on I&I method. The configuration of I&I method on induction motor has been shown in figure 1.

First, tracking errors are defined and errors should become stable reaching to 0 based on our control objective. Hence, we define the errors variables such as:

$$e_1 = x_1 - r_1$$
$$e_2 = x_2 - r_2 \qquad (5)$$

Considering the error dynamic, the control objective is that e_1 and e_2 reach to 0; since we do not know values of θ_1 and θ_2, these parameters are uncertain.

So, let have

$$\dot{e}_1 = \left[\mu e_2 x_4 + \mu r_2 x_4 - a_1 + \dot{r}_1\right] + b_1\theta_1$$
$$\dot{e}_2 = \left[-a_2 e_2 - a_2 r_2 + a_3 x_3 + \dot{r}_2\right] + \left[b_2 e_2 + b_2 r_2 + b_3 x_3\right]\theta_2$$
$$\dot{x}_3 = \left[a_4 e_2 + a_4 r_2 - a_5 x_3 + e_1 x_4 + r_1 x_4 + a_6 x_4^2 / \left(e_2 + r_2\right)\right] + \left[b_4 e_2 + b_4 r_2 + b_5 x_3 + b_6 x_4^2 / \left(e_2 + r_2\right)\right]\theta_2 + \frac{1}{L_1}u_1$$
$$\dot{x}_4 = \left[-\beta e_1 e_2 - \beta e_1 r_2 - \beta r_1 e_2 - \beta r_1 r_2 - a_5 x_4 - e_1 x_3 - r_1 x_3 + a_6 x_3 x_4 / \left(e_2 + r_2\right)\right] + \left[b_5 x_4 + b_6 x_3 x_4 / \left(e_2 + r_2\right)\right]\theta_2 + \frac{1}{L_1}u_2$$

(6)

To design controller, an adaptive algorithm was designed based on principles of I&I method; according to primitive principles of I&I method [2, 3], following steps should be taken:

$$e_1 = \eta_1$$
$$e_2 = \eta_2$$
$$x_3 = \pi_3\left(\eta_1, \eta_2\right)$$
$$x_4 = \pi_4\left(\eta_1, \eta_2\right) \qquad (7)$$

Verification of (H1)

Moreover, target system is considered as follows:

$$\dot{\eta}_1 = -\lambda_1 \eta_1$$
$$\dot{\eta}_2 = -\lambda_2 \eta_2 \qquad (8)$$

Now, equations (6) and (8) are used:

$$-\lambda_1 \eta_1 = \left[\left(\mu e_2 + \mu r_2\right)\pi_4 - a_1 + \dot{r}_1\right] + b_1\theta_1$$
$$-\lambda_2 \eta_2 = \left[-a_2 e_2 - a_2 r_2 + a_3 \pi_3 + \dot{r}_2\right] + \left[b_2 e_2 + b_2 r_2 + b_3 \pi_3\right]\theta_2 \qquad (9)$$

Verification of (H2)

Using equation (9), mapping π (ξ) was obtained:

$$\pi_4 = \left(-\lambda_1 \eta_1 + a_1 - \dot{r}_1 - b_1\theta_1\right) / \left(\mu e_2 + \mu r_2\right)$$
$$\pi_3 = \left(-\lambda_2 \eta_2 + a_2 e_2 + a_2 r_2 - \dot{r}_2 - \left(b_2 e_2 + b_2 r_2\right)\theta_2\right) / \left(b_3\theta_2 + a_3\right) \qquad 10)$$

Verification of (H3)

Considering equation (10), φ_1 and φ_2 are defined as follows:

$$\varphi_1 : x_4 - \left(-\lambda_1 e_1 + a_1 - \dot{r}_1 - b_1\theta_1\right) / \left(\mu e_2 + \mu r_2\right) = 0$$
$$\varphi_2 : x_3 - \left(-\lambda_2 e_2 + a_2 e_2 + a_2 r_2 - \dot{r}_2 - \left(b_2 e_2 + b_2 r_2\right)\theta_2\right) / \left(b_3\theta_2 + a_3\right) = 0 \qquad (11)$$

Verification of (H4)

Since values of θ_1 and θ_2 are not known and they are uncertain, their estimation values $\hat{\theta}_1$ and $\hat{\theta}_2$ are used instead of θ_1 and θ_2 then will have based on the fourth step of I&I method:

$$\dot{\xi}_1 = \dot{x}_4 - \frac{\left(-\lambda_1 \dot{e}_1 - \ddot{r}_1 - b_1\dot{\hat{\theta}}_1\right)\left(\mu e_2 + \mu r_2\right) - \left(-\lambda_1 e_1 + a_1 - \dot{r}_1 - b_1\hat{\theta}_1\right)\left(\mu \dot{e}_2 + \mu \dot{r}_2\right)}{\left(\mu e_2 + \mu r_2\right)^2}$$

(12)

$$\dot{\xi}_2 = \dot{x}_3 - \Big[\left(-\lambda_2 \dot{e}_2 + a_2\dot{e}_2 + a_2\dot{r}_2 - \ddot{r}_2 - \left(b_2\dot{e}_2 + b_2\dot{r}_2\right)\hat{\theta}_2 - \left(b_2 e_2 + b_2 r_2\right)\dot{\hat{\theta}}_2\right)\left(b_3\hat{\theta}_2 + a_3\right) - \left(-\lambda_2 e_2 + a_2 e_2 + a_2 r_2 - \dot{r}_2 - \left(b_2 e_2 + b_2 r_2\right)\hat{\theta}_2\right) b_3\dot{\hat{\theta}}_2\Big] \Big/ \left(b_3\hat{\theta}_2 + a_3\right)^2$$

Replace equation (6) instead of $\dot{x}_3$ and $\dot{x}_4$:

$$\dot{\xi}_1 = \left[-\beta e_1 e_2 - \beta e_1 r_2 - \beta r_1 e_2 - \beta r_1 r_2 - a_5 x_4 - e_1 x_3 - r_1 x_3 + a_6 x_3 x_4 / \left(e_2 + r_2\right)\right] + \left[b_5 x_4 + b_6 x_3 x_4 / \left(e_2 + r_2\right)\right]\theta_2 + \frac{1}{L_1}u_2 - \frac{\left(-\lambda_1 \dot{e}_1 - \ddot{r}_1 - b_1\dot{\hat{\theta}}_1\right)\left(\mu e_2 + \mu r_2\right) - \left(-\lambda_1 e_1 + a_1 - \dot{r}_1 - b_1\hat{\theta}_1\right)\left(\mu \dot{e}_2 + \mu \dot{r}_2\right)}{\left(\mu e_2 + \mu r_2\right)^2}$$

$$\dot{\xi}_2 = \left[a_4 e_2 + a_4 r_2 - a_5 x_3 + e_1 x_4 + r_1 x_4 + a_6 x_4^2 / \left(e_2 + r_2\right)\right] + \left[b_4 e_2 + b_4 r_2 + b_5 x_3 + b_6 x_4^2 / \left(e_2 + r_2\right)\right]\theta_2 + \frac{1}{L_1}u_1 - \Big[\left(-\lambda_2 \dot{e}_2 + a_2\dot{e}_2 + a_2\dot{r}_2 - \ddot{r}_2 - \left(b_2\dot{e}_2 + b_2\dot{r}_2\right)\hat{\theta}_2 - \left(b_2 e_2 + b_2 r_2\right)\dot{\hat{\theta}}_2\right)\left(b_3\hat{\theta}_2 + a_3\right) - \left(-\lambda_2 e_2 + a_2 e_2 + a_2 r_2 - \dot{r}_2 - \left(b_2 e_2 + b_2 r_2\right)\hat{\theta}_2\right) b_3\dot{\hat{\theta}}_2\Big] \Big/ \left(b_3\hat{\theta}_2 + a_3\right)^2$$

(12)

To design adaptive control and adaptation analysis at this step, following steps should be taken:
First, the following definitions should be considered:

$$\begin{aligned} z_1 &= \hat{\theta}_1 + \vartheta_1\left(e_1, e_2\right) - \theta_1 \\ z_2 &= \hat{\theta}_2 + \vartheta_2\left(e_1, e_2\right) - \theta_2 \\ \dot{\hat{\theta}}_1 &= \psi_1 \\ \dot{\hat{\theta}}_2 &= \psi_2 \end{aligned} \quad (13)$$

Therefore, considering equations (12) and (13), let have:

$$u_2 = -\gamma\xi_1$$
$$-L_1\left[-\beta e_1 e_2 - \beta e_1 r_2 - \beta r_1 e_2 - \beta r_1 r_2 - a_5 x_4 - e_1 x_3 - r_1 x_3 + a_6 x_4^2 / \left(e_2 + r_2\right)\right]$$
$$-L_1\left[b_5 x_4 + b_6 x_4^2 / \left(e_2 + r_2\right)\right]\left(\hat{\theta}_2 + \vartheta_2\left(e_1, e_2\right)\right)$$
$$+L_1 \frac{\left(-\lambda_1 \dot{e}_1 - \ddot{r}_1 - b_1\psi_1\right)\left(\mu e_2 + \mu r_2\right) - \left(-\lambda_1 e_1 + a_1 - \dot{r}_1 - b_1\hat{\theta}_1\right)\left(\mu\dot{e}_2 + \mu\dot{r}_2\right)}{\left(\mu e_2 + \mu r_2\right)^2}$$

(14)
$$u_1 = -\gamma\xi_2$$
$$-L_1\left[a_4 e_2 + a_4 r_2 - a_5 x_3 + e_1 x_4 + r_1 x_4 + a_6 x_3 x_4 / \left(e_2 + r_2\right)\right]$$
$$-L_1\left[b_4 e_2 + b_4 r_2 + b_5 x_3 + b_6 x_3 x_4 / \left(e_2 + r_2\right)\right]\left(\hat{\theta}_2 + \vartheta_2\left(e_1, e_2\right)\right)$$
$$+L_1\left[\left(-\lambda_2 \dot{e}_2 + a_2 \dot{e}_2 + a_2 \dot{r}_2 - \ddot{r}_2 - \left(b_2 \dot{e}_2 + b_2 \dot{r}_2\right)\hat{\theta}_2 - \left(b_2 e_2 + b_2 r_2\right)\psi_2\right)\left(b_3\hat{\theta}_2 + a_3\right)\right.$$
$$\left.-\left(-\lambda_2 e_2 + a_2 e_2 + a_2 r_2 - \dot{r}_2 - \left(b_2 e_2 + b_2 r_2\right)\hat{\theta}_2\right) b_3\psi_2\right] \Big/ \left(b_3\hat{\theta}_2 + a_3\right)^2$$

Where; γ refers to positive and constant parameter. Obviously, replacing this control rule, dynamic (12) is stable.

To find adaptation rules, according to following definitions related to z_1 and z_2 in equation (13) we have:

(15)
$$\dot{z}_1 = \psi_1 + \frac{\partial\vartheta_1}{\partial e_1}\left(\left[\mu e_2 x_4 + \mu r_2 x_4 - a_1 + \dot{r}_1\right] + b_1\left(\hat{\theta}_1 + \vartheta_1 - z_1\right)\right)$$
$$+\frac{\partial\vartheta_1}{\partial e_2}\left(\left[-a_2 e_2 - a_2 r_2 + a_3 x_3 + \dot{r}_2\right] + \left[b_2 e_2 + b_2 r_2 + b_3 x_3\right]\left(\hat{\theta}_2 + \vartheta_2 - z_2\right)\right)$$
$$\dot{z}_2 = \psi_2 + \frac{\partial\vartheta_2}{\partial e_1}\left(\left[\mu e_2 x_4 + \mu r_2 x_4 - a_1 + \dot{r}_1\right] + b_1\left(\hat{\theta}_1 + \vartheta_1 - z_1\right)\right)$$
$$+\frac{\partial\vartheta_2}{\partial e_2}\left(\left[-a_2 e_2 - a_2 r_2 + a_3 x_3 + \dot{r}_2\right] + \left[b_2 e_2 + b_2 r_2 + b_3 x_3\right]\left(\hat{\theta}_2 + \vartheta_2 - z_2\right)\right)$$

According to equation above, ψ_1 and ψ_2 is calculated as follows

(16)
$$\psi_1 = -\frac{\partial\vartheta_1}{\partial e_1}\left(\left[\mu e_2 x_4 + \mu r_2 x_4 - a_1 + \dot{r}_1\right] + b_1\left(\hat{\theta}_1 + \vartheta_1\right)\right)$$
$$-\frac{\partial\vartheta_1}{\partial e_2}\left(\left[-a_2 e_2 - a_2 r_2 + a_3 x_3 + \dot{r}_2\right] + \left[b_2 e_2 + b_2 r_2 + b_3 x_3\right]\left(\hat{\theta}_2 + \vartheta_2\right)\right)$$
$$\psi_2 = -\frac{\partial\vartheta_2}{\partial e_1}\left(\left[\mu e_2 x_4 + \mu r_2 x_4 - a_1 + \dot{r}_1\right] + b_1\left(\hat{\theta}_1 + \vartheta_1\right)\right)$$
$$-\frac{\partial\vartheta_2}{\partial e_2}\left(\left[-a_2 e_2 - a_2 r_2 + a_3 x_3 + \dot{r}_2\right] + \left[b_2 e_2 + b_2 r_2 + b_3 x_3\right]\left(\hat{\theta}_2 + \vartheta_2\right)\right)$$

Replacing equation (16) in equation (15), following equation is obtained:

(17)
$$\dot{z}_1 = -\frac{\partial\vartheta_1}{\partial e_1}\left(b_1 z_1\right) - \frac{\partial\vartheta_1}{\partial e_2}\left(\left[b_2 e_2 + b_2 r_2 + b_3 x_3\right] z_2\right)$$
$$\dot{z}_2 = -\frac{\partial\vartheta_2}{\partial e_1}\left(b_1 z_1\right) - \frac{\partial\vartheta_2}{\partial e_2}\left(\left[b_2 e_2 + b_2 r_2 + b_3 x_3\right] z_2\right)$$

To have sustainable dynamic of equation (17), ϑ_1 and ϑ_2 are selected as follows:

(18)
$$\vartheta_1 = -e_1$$
$$\vartheta_2 = \int_0^{e_2} \left[b_2\chi + b_2 r_2 + b_3 x_3 \right] d\chi = \frac{1}{2} b_2 e_2^2 + b_2 r_2 + b_3 x_3$$

According to equation (18), dynamic of (17) is sustainable obviously:

(19)
$$\dot{z}_1 = b_1 z_1$$
$$\dot{z}_2 = -\left[b_2 e_2 + b_2 r_2 + b_3 x_3 \right]^2 z_2$$

Note that $b_1 = -\frac{n_p}{J} < 0$

Adaptation rules of (16) are simplified as follows:

(20)
$$\psi_1 = \left(\left[\mu e_2 x_4 + \mu r_2 x_4 - a_1 + \dot{r}_1 \right] + b_1 \left(\hat{\theta}_1 + \vartheta_1 \right) \right)$$
$$\psi_2 = -\left(b_2 e_2 + b_2 r_2 + b_3 x_3 \right) \left(\left[-a_2 e_2 - a_2 r_2 + a_3 x_3 + \dot{r}_2 \right] + \left[b_2 e_2 + b_2 r_2 + b_3 x_3 \right] \left(\hat{\theta}_2 + \vartheta_2 \right) \right)$$

According to the obtained adaptation rule, sustainable closed loop system is asymptotic and control objectives are achieved.

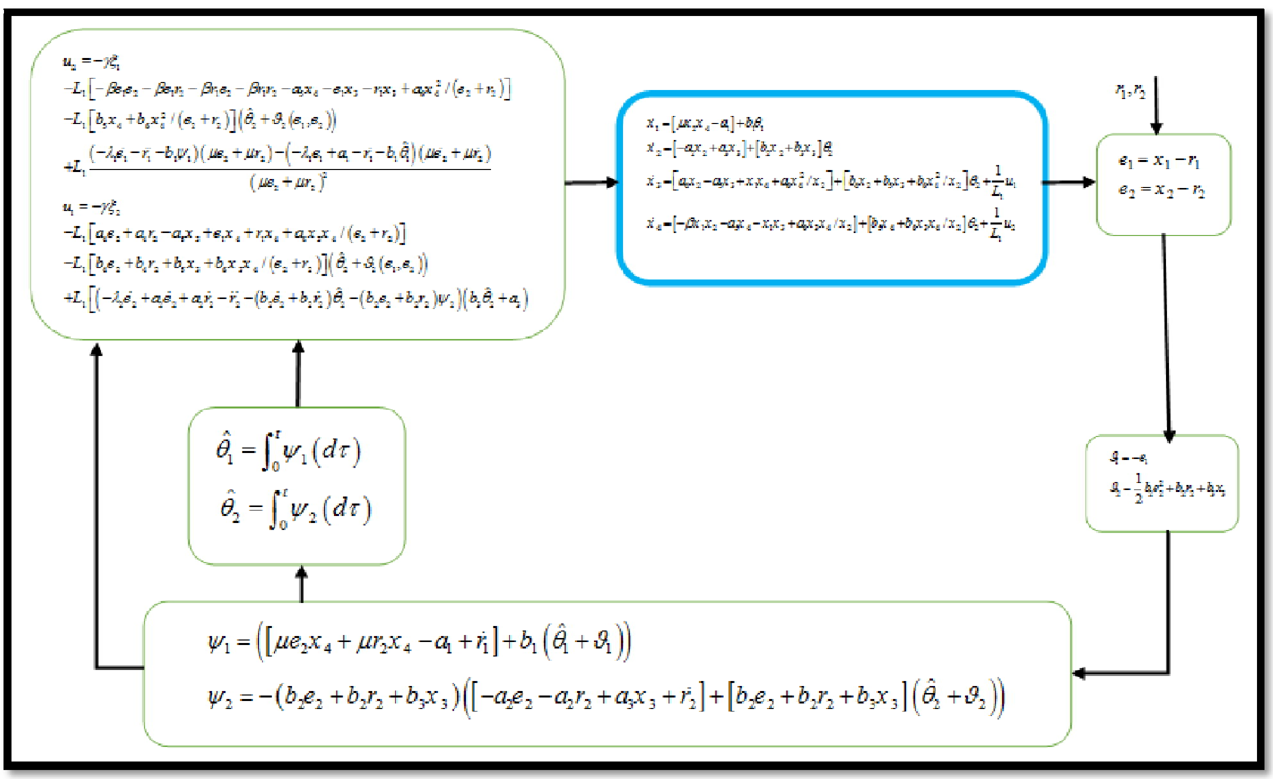

Figure 2: Implementation Block of I&I Method

4. Simulation Experiment

To indicate performance and results of suggested controller, simulation was implemented through MATLAB software and all nominal mechanic and electric specifications of motor are showed in table 1. To design controller, there are two types of faults as uncertainties in system model that rotor resistance is changed based on the equation $R_r = R_{rN} + R_{rN}\left(1 - \exp\left(-1.2t\right)\right)$ in order to examine faults and as it is indicated in figure 3, load torque changes are shown. Load torque will be changed 3 seconds after its nominal value ((T_{rN} = 5Nm). Reference values are considered for induction motor speed (ω_{ref} = 200rd/s) and rotor magnetic flux ($\varnothing_{ref}$ = 1Wb). Simulation results have been examined as follows:

Description	Parameter	Value	Units
Stator resistance	R_s	1.2	Ω
Rotor resistance	R_r	1	Ω
Stator inductance	L_s	0.1554	H
Rotor inductance	L_r	0.1568	H
Rated load	T_{rN}	5	N_m
Rated speed	-	1480	rpm
Mutual inductance	M_{sr}	0.15	H
Number of pole pairs	n_p	2	-
Rotor inertia	J	0.013	Kg m^2

Table 1: Parameter Values of Motor [33,34]

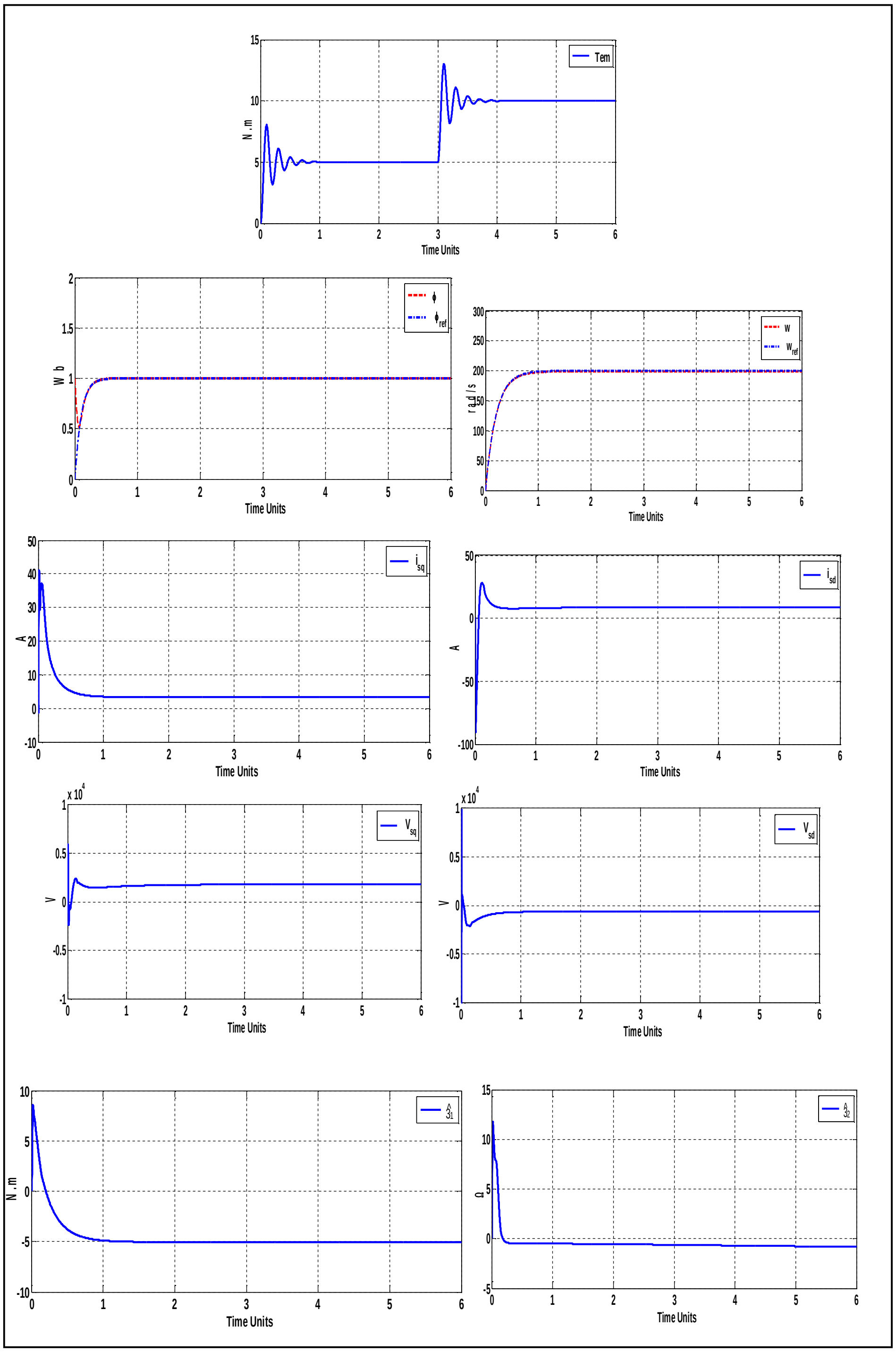

Figure 3

As it is shown in figure 4, the speed has tracked desired reference with defined value of (ω_{ref} = 200rd/s) as well and figure 5 indicates that rotor magnetic flux can well track the desired reference with defined value of ($\emptyset_{ref}$ = 1Wb). Under fault conditions in which, load torque is suddenly changed at 3 second and rotor resistance value is changed exponentially with slow changes due to skin effect and warming, reference tracking has been formed for them rapidly and signals are completely smooth. In this case, excellent performance of controller is indicated, so that the system is completely sustainable while uncertain parameters are considered in the IM model. Figures 6 and 7 illustrate stator current that fault effects have been ineffective for them. Figures 8 and 9 depict control signals and since smoothness of control signals is a significant point in control engineering and implementation of practical issues, they have no oscillation with suitable behavior. Considering the presence of uncertain parameters in induction motor model and their changes through time, they have been estimated based on adaptation rules. Figures 10 and 11illustarte ξ parameters estimated by controller achieving a good estimation.

As it was proved, tracking speed and rotor flux reference signals, and estimating variable parameters using this new suggested method has presented a complete examination of system behavior studying control issue,. According to the simulation results, it is simply observed that proposed controller can perform control objectives perfectly. Moreover, highly favorable behavior of input control signals as well as lack of fluctuations has led to extensive use of this method in practical applications so it is a reliable method.

5. Conclusion

In this paper, widely used non-linear system of induction motor has been studied and a new and efficient adaptive controller that is distinguished from previous methods has been introduced for system based on Immersion and Invariance (I&I) method. To design controller, induction motor system has been considered in error mode and the considered errors in system have led to motor's uncertain dynamic making it difficult to control induction motor. Accordingly, controller has been designed adaptively and the named parameters- that may be changed under working conditions of motor during time- are estimated online. Adaptive rules are obtained from stability analysis based of I&I method. According to the results obtained from simulation in MATLAB, it will be possible to see effectiveness of controller obviously that is able to track optimal path also to generate suitable control signals in presence of unknown parameters in system model.

An adaptive non-linear controller was proposed for a class of induction motors. The adaptive mechanism is based on I&I method which provide a modern solution to design adaptive control of induction motor with uncertain dynamic. The dynamic of IM studied under faulty condition and load torque and rotor resistance were considered as uncertainties in the IM system. The parameters that may change during motor operation were estimated online. Adaptive rules were obtained from stability analysis based on I&I method. The offered adaptive controller due to its capability to tracking the speed and the rotor magnetic flux desired references with regard to parameter variations can be presented as a suitable technique with excellent performance for induction motor system in practical applications. Effectiveness and suitable performance of suggested controller was verified by simulation results.

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