International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 13, No. 3, September 2022, pp. 1459~1468
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v13.i3.pp1459-1468

Online induction motor rotor time constant estimation using perturbation-based extremum seeking control

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Article Info

Article history:

Received Apr 3, 2022
Revised May 25, 2022
Accepted Jun 14, 2022

Keywords:

Active power function
Extremum seeking control
Induction motor
Parameter estimation

ABSTRACT

A novel online induction motor (IM) rotor time constant estimator based on a perturbation-based extremum seeking control (ESC) and model reference adaptive system (MRAS) is proposed. Since implementations of field-oriented control (FOC) requires accurate values of IM parameters, such as rotor time constant, so accurate and robust on-line estimations of such parameters are crucial for any modern industrial IM drives. The proposed MRAS estimator employs ESC method to estimate the IM rotor resistance in various operating conditions. Meanwhile, since extremum seeking control is a model-free scheme, so it is robust to other IM parameter variations. The feasibility and effectiveness of the IM rotor resistance estimation by utilizing ESC scheme has been verified by simulation and experimental results. A 2.2 kW experimental setup has been implemented.

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1. INTRODUCTION

Since induction motors (IMs) have low cost, high efficiency, and high reliability, so, they are widely utilized in various industrial applications including AC servo systems, compressors, fans, pumps, and electrical vehicles (EV). The scalar or constant v/f control, vector control and direct torque control (DTC) are the most applied control methods to the induction motor IM drives. The indirect implementations of field- oriented control FOC (IFOC) is considered as a high-performance and more applicable control method among the various provided IM drive systems. The IFOC needs rotor flux values for IM control which normally are not directly measured. Hence, the rotor time constant is required to obtain for proper flux orientation in IFOC [1], [2]. In IM, both rotor leakage inductance (L_r) and rotor resistance (R_r) vary according to the IM operation conditions. Even though, the L_r can be extracted online by magnetizing curve, $R_r$strongly depends on skin effect and the rotor temperature. The R_r variation may be about 100% based on the motor temperature and rotor frequency. Therefore, the wide range variations of R_r and L_r leads to considerable mismatch in rotor time constant (τ_r) value and rotor flux orientation, which deteriorates the dynamic and steady-state performance of the IM drive. So, the τ_r online estimation is vital for proper operation of IFOC based IM drive.

Various estimation methods including signal injection method, full-order observer, extended Kalman filter, sliding mode method, stochastic methods, artificial intelligent based methods, and MRAS-based methods have been introduced in the literature [3]-[5]. The MRAS method is more popular because of its simple implementation and structure. In the MRAS method, one IM quantity is calculated by two various functions in which one of them depends on τ_r and another one is independent of the τ_r. The selected quantity of the IM can be stator voltage, rotor flux, electromagnetic torque, and or active/reactive powers. Then, the error between the outputs of two functions is applied to the controller to provide the estimated value of τ_r. The applied controller can be integral (I) or proportional-integral (PI) to obtain the estimated value. Wade *et al.* [6] and [7], the rotor flux has been employed to the MRAS estimation. Wade *et al*. [6], the *d* axis rotor flux has been employed for estimation instead of *q* axis rotor flux whereas in [7], the resistance of rotor is estimated to set the *q* axis rotor flux to zero. The electro-magnetic torque has been utilized to identify the rotor resistance in [8], where the MRAS based on the electro-magnetic torque can be used in transient conditions. However, due to the integrator usage in calculation of the stator fluxes in *d-q* frame, this method suffers from integrator related problems such as dc offset and saturation. The IM reactive power formula which is not related to the variation of stator resistance presented in [9], [10]. Maiti *et al*. [9], the rotor resistance estimation method that is robust to stator resistance variations verified by various results. The MRAS based on the flux eliminated reactive power has been suggested in [9] for IM rotor resistance identification. However, due to the usage of reactive power, the estimation performance is not good enough during the transient time. Garces [11], the function of the reactive power has been employed for τ_r estimation. Not only does the presented function depend on the stator currents and voltages, but also it is indirectly related to the mutual, stator, and rotor inductances. Hence, the estimated $\tau_r$value depends on the IM torque and frequency. IM drive parameters estimation using active and reactive powers based model reference adaptive system MRAS has been proposed in [12]. The robustness of proposed scheme has been investigated to load and magnetizing inductance variations.

Moreover, PI or I controller precision has been affected by the nonlinear behavior and wide range variations of IM parameters. Hence, the accuracy of the estimated τ_r value depends on the operating point of the IM. In order to overcome this drawback, model independent nonlinear controller can be used to estimate the τ_r value. The extremum seeking control ESC is an adaptive optimization method which does not require the plant model for any parameter estimation of IM. By applying a small sinusoidal disturbance signal, and an adaptive search, the ESC method detects the optimum control rule or optimum operating point of the plant by using the dynamic feedback. The ESC is a robust scheme because it is plant model free [13], [14]. Over the last decade ESC had considerable attention in optimum control process. This method, which dates back to the year of 1920s, is a model independent nonlinear controller [15]. An effective control system approach can be provided by ESC that can be used to optimize a cost function by conducting an unknown dynamic system to an equilibrium point. There are some limitations for ESC, so, many research works have been conducted various approaches to overcome these limitations. Detailed performance limitations related to ESC were presented in [16]. More details on the guarantees of convergence and tighter bounds on the tuning parameters were proposed. A time-varying identification-based ESC approach is proposed in [17]. This approach tries to overcome the ESC limitations related to the difficult tuning of the ESC parameters. In this technique, by using a time-varying gradient estimation approach the ESC tuning problem is solved in such a way that it avoids the limitations related to the averaging nature of ESC. Guay and Burns [18], two classes of ESC approaches were investigated: Time-varying and perturbation-based ESC methods. While it was easier to tune the perturbation-based method, but in some situations, the optimum was not obtained. The time-varying ESC was converging more reliably and faster than the other method. Optimum reference flux searching for DTC of interior permanent magnet synchronous motor IPMSM by ESC has been proposed in [19]. Optimum stator flux will lead to maximum torque- per- ampere approach and higher efficiency. ESC optimal approach has been proposed to improve the energy performance of an IM electric drive with frequency-current control [20]. By adjusting the stator voltage by optimal manner, the motor will operate on critical slip and minimum current consumption will be achieved. The proposed method’s effectiveness has been verified just by simulations. Meanwhile the stability of proposed scheme has not been discussed and analyzed. Various MPPT methods for PVs based on ESC are presented in [21], [22]. The ESC method provides excellent steady state performance and very fast convergence by tuning the solar PV arrays’ current or voltage in order to maximize the output power. Individual ESC, which optimizes the power of the single wind turbines separately has been proposed in [23]. Since the ESC is model-free, atmospheric conditions uncertainties, and aging of the wind turbine should not change the overall conclusions obtained in this paper. This technique can provide acceptable results and model-free approach to power optimization.

In the present paper, a new MRAS based IM rotor time constant estimator by using a perturbation based ESC method is proposed. The modified active power function is robust to any noise, because the adjustable and reference models have the same function and the same inputs. Therefore, the noises will be cancelled out by the MRAS comparator. Moreover, the perturbation based ESC and MRAS method is proposed to obtain accurate rotor resistance estimation during a wide range variation of rotor resistance. Because of utilizing the perturbation based ESC, this technique is robust to the IM stator resistance and magnetizing inductance variations. Based on our knowledge application of the ESC in IM parameter estimation has not been investigated yet. The main contributions of the proposed method are:

- It is robust to any noise from the switching devices, as both the adjustable and reference models have the same function, so the noises will be cancelled out by the MRAS comparator.
- The online rotor resistance estimation based on ESC is robust and it is independent from IM parameters.
- Application of ESC for IM parameter estimations.

This paper is organized as following. Section 2, presented the research method with theoretical analysis of IM model and MRAS scheme. Also in this section, ESC algorithm for optimal rotor resistance estimation is presented along with stability analysis. Simulation and experimental results of robust rotor resistance identification are presented in section 3.

2. RESEARCH METHOD

2.1. IM dynamic model

The IM Model in stationary $d-q$ reference frame is:

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} v_s = Ax + Bv_s \tag{1}$$

$$i_s = Cx \tag{2}$$

where $i_s = [i_{ds} \quad i_{qs}]^T$ and $v_s = [v_{ds} \quad v_{qs}]^T$ are the stator current and voltage vectors, respectively. $\varphi_r = [\varphi_{dr} \quad \varphi_{qr}]^T$ is the rotor flux vector and $x = [i_s \quad \varphi_r]^T$ is the state vector. The state space coefficients of (1) and (2) are:

$$A_{11} = -\left[\frac{R_1}{\sigma L_1} + \frac{1-\sigma}{\sigma \tau_r}\right] I = a_{r11} I A_{12} = \frac{L_m}{\sigma L_1 L_2}\left[\frac{1}{\tau_r} I - \omega_r J\right] = a_{r12} I + a_{r12} J \tag{3}$$

$$A_{21} = \frac{L_m}{\tau_r} I = a_{r21} I, A_{22} = -\frac{1}{\tau_r} I + \omega_r J \text{ B} = \frac{1}{\sigma L_1} I = b_1 I, C = [I \quad 0] \tag{4}$$

where $I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ and $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$. L_1 , R_1 and L_2,R_2 are the inductances and resistances of stator and rotor, respectively, and L_m is mutual inductance. Moreover, $\sigma = 1 - \frac{L_m^2}{L_1 L_2}$ is the leakage inductance coefficient and $\tau_r = \frac{L_2}{R_2}$ is the rotor time constant

2.2. Active power-based MRAS scheme

The IM's active power has been obtained in two different ways in the MRAS based $\tau_r$value estimation. In the MRAS-based $\tau_r$value estimator, one approach (equation) for active power calculation depends on the $\tau_r$whereas another approach is independent of $\tau_r$value. Then, the error signal between the outputs of two active power calculations is applied to the perturbation-based ESC. The output of the ESC presents the estimated parameter $\hat{R_r}$ value. The overall block diagram of the proposed MRAS using the perturbation-based ESC is presented in Figure 1. The measured $V_s^*$and I_s^*values of IM are employed to calculate the reference model (active power) of IM in (5). Therefore, by employing the measured amounts of currents and voltages, the true value of IM active power (P^*) are always provided by a reference model. Hence, the reference model (P^*) of the IM is expressed as (5).

$$P^* = \frac{3}{2}\left(v_{ds}^* i_{ds}^* + v_{qs}^* i_{qs}^*\right) \tag{5}$$

Where v_{ds}^*, v_{qs}^*, i_{ds}^* and i_{qs}^* will be measured from induction motor's terminals. In order to define the adjustable IM model based on active power function the $\left(\hat{i_{ds}}, \hat{i_{qs}}\right)$ are obtained from IM model in (1). So, the adjustable model of IM based on the active power function is written as (6).

$$\mathrm{P_{adj}} = \frac{3}{2}\left(\mathrm{v_{ds}^* \hat{i}_{ds} + v_{qs}^* \hat{i}_{qs}}\right) \tag{6}$$

Where ^ indicates the estimated values from IM model of (1) and * shows the measured value from IM terminals. As presented in (1), the adjustable model depends on the IM parameters such as $\hat{R_r}$. Moreover, because both adjustable and reference models have the same inputs (voltages), any mismatch in the $\hat{R_r}$ value leads to an error in P_{adj} compared to the reference value of P^* (5). ε which is th e error between P^* and P_{adj} , is applied to the proposed perturbation based ESC as shown in Figure 1. The $\hat{R_r}$ value is converging to an actual value by compensating the ε by ESC controller (converging P^* to P_{adj}, and ε = 0). Since we put the measured values instead of calculated values for v_{ds}^*, v_{qs}^* in the P_{adj}, so by this modification the adjustable model has less dependent on motor parameters. This function is called modified active power function in this research work.

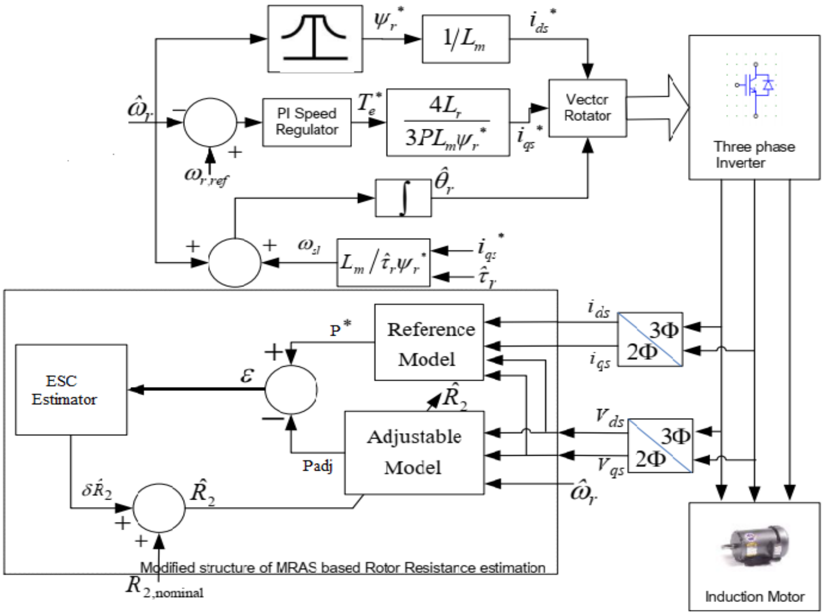


Figure 1. Block diagram of IM overall control system

2.3. Perturbation based extermum seeking control

The ESC is an adaptive optimization technique which does not require the plant model for optimizing input-output characteristics of plant. By applying small sinusoidal disturbance signal, and adaptive search, the ESC method detects the optimum control rule or optimum operating point of the plant by using the dynamic feedback. The ESC method is robust because it is independent of the plant model and can be applied to various applications. The algorithm of the perturbation based ESC is shown in Figure 2. As presented in this figure, the ESC generates small amplitude with high frequency periodic perturbation (dither) signal $a \times sin(\omega t)$ and adds this signal to the estimated $\hat{\theta}$ value. Here, y (cost function) represents the active power error signal, ε, (ε represents the P^* - P_{adj} error) and θ is the estimated rotor resistance $\hat{R_r}$. If θ is near to optimum θ^* value, $a \times sin(\omega t)$ generates a periodic response of y. The high-pass filter is used to eliminate DC value of y resulting the both $a \times sin(\omega t)$ and high-pass filter output are approximately sinusoidal. Then low pass filter removes all high frequency elements. Here integrator acts as PI controller and will force the χ to be zero, this process will continue until the $\hat{\theta}$ be equal to real value θ^* (real R_r^*). χ $d\hat{\theta}/dt\gamma$ is the gradient estimation, at extremum point the χ will reach to zero (Low pass filter's output indicates the $\frac{a^2}{2}\frac{d\varepsilon}{dR_r}$, gradient of active power error, and the integrator will force it to be zero at minimum value of ε). As shown in Figure 3, when IM operate on the left-hand side of the operating point, $\frac{d\varepsilon}{dR_r}$ is negative, while when IM works on the right-hand side of the operating point, $\frac{d\varepsilon}{dR_r}$ is positive. If IM operates exactly at minimum value of ε , $\frac{d\varepsilon}{dR_r}$ is 0. The cost function of ESC estimator is as (7).

$$\varepsilon = \mathrm{e} = P^{*} - P^{\wedge} = \frac{3}{2}\left(v_{ds}^{*} i_{ds}^{*} + v_{qs}^{*} i_{qs}^{*}\right) - \frac{3}{2}\left(v_{ds}^{*} i_{ds}^{\wedge} + v_{qs}^{*} i_{qs}^{\wedge}\right) \quad (7)$$

Where $P^{\wedge} = P_{adj}$. Based on Figures 1, 2, 3 the ESC estimator will force the e (ε) to be zero by approaching the $R_r^{\wedge}$ to R_r (real rotor resistance). In this case the cost function in (7) will be zero.

2.4. Stability analysis of ESC

Any C^2 function of $Y(\theta)$ can be approximated by (8).

$$Y(\theta) = f^{*} + k.(\theta - R_r^{*})^2 \quad (8)$$

Where $Y(\theta)$ is output function (active power error), $k > 0$, and R_r^{*} is optimal (real) value of IM's rotor resistance. $f^{*}$is the optimal value of Y when rotor resistance estimated value converges to the real one. The purpose of the algorithm is to make $\theta - R_r^{*}$ as small as possible, so that the function Y is driven to its minimum value f^{*}(in this situation the active power error, cost function, will be driven to zero). Let:

$$q = R_r^{*} - R_r^{\wedge} \quad (9)$$

Denotes the estimation error. Since based on Figure 2 we have:

$$\theta = R_r^{\wedge} + asin\ (\omega t) \quad (10)$$

So, the estimation error summarizes as:

$$\theta - R_r^{*} = axsin(\omega t)\text{-}q \quad (11)$$

Substitution of (11) into (8), gives:

$$Y(\theta) = f^{*} + k.(q - \mathrm{asin}\ (\omega t))^2 \quad (12)$$

Expanding this equation, and applying high pass filter gives:

$$J \approx kq^2 \text{-} k\frac{a}{2}\cos(2\omega t) - 2kqasin(\omega) \quad (13)$$

f^{*} and $ka/2$ will be removed by high pass filter. This signal demodulated by multiplication with sin(ωt), giving:

$$v \approx kq^2 \sin\ (\omega t) \text{-}\ k\frac{a}{2}\cos(2\omega t)\sin\ (\omega t) - 2kqasin(\omega)sin(\omega t) \quad (14)$$

Since ω is large enough, so by applying low pass filter all high frequency elements will be removed from v. By simplification and applying low pass filter we will have the:

$$\chi \approx -kqa \quad (15)$$

Since at optimum point the R_r^{*} is constant so derivating both sides of (9) gives:

$$q^{\cdot} \approx \text{-}R_r^{\wedge\cdot} \quad (16)$$

Where $q^{\cdot}$, and $R_r^{\wedge\cdot}$ are derivative values of q and $R_r^{\wedge}$, respectively. So based on (15) and (16) we will get:

$$q \approx \frac{\gamma}{s}[-kqa] \quad (17)$$

or:

$$q^{\cdot} \approx -ka\gamma q \quad (18)$$

Since $ka\gamma > 0$, so this is a stable system (the root is located at the left-hand side of the imaginary axis). So, we conclude that q will converge to zero and consequently $R_r^{\wedge}$ *to* R_r^{*} and $Y(\theta)$ (cost function) to f^{*}. From above equations it is important to note that our approximations hold only when ω is large enough compared to $k, a, and\, \gamma$ [24]. Reduction of the dither frequency ω will slow the convergence speed. Consequently, the transient response is slower and convergence is longer.

2.5. Comparison

Comparison has been made between proposed method and the other schemes in terms of IM's rotor resistance settling (estimation) time and robustness to stator resistance variations. The comparison results are summarized at the Table 1. From this table one can see that all methods are robust to stator resistance variations. However, proposed perturbation-based ESC method has lower settling time for rotor resistance identification compared to reactive power- based MRAS method in [9], a ninth-order estimation algorithm based simultaneous estimation of rotor and stator resistances in [25], and direct rotor flux identification -based scheme in [26]. So, perturbation-based ESC method not only provides faster estimation scheme but also it is robust to stator resistance variations. Since ESC method is model free, so it is robust to all IM parameters, including magnetizing inductance, inertia, and load torque variations.

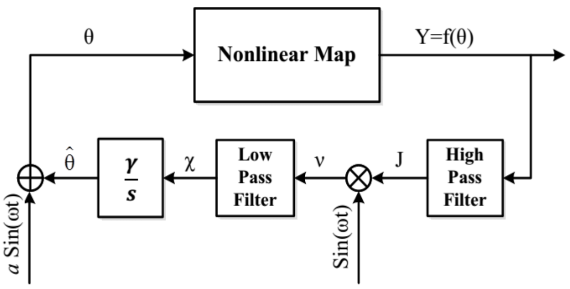


Figure 2. Perturbation based extrimum seeking control

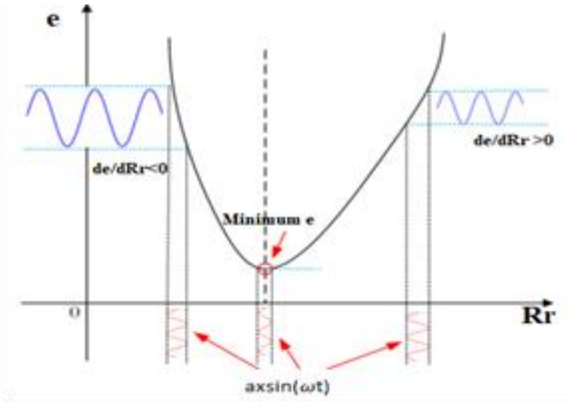


Figure 3. Injection of dither signal to rotor resistance

Table 1. Comparison between proposed and previous methods

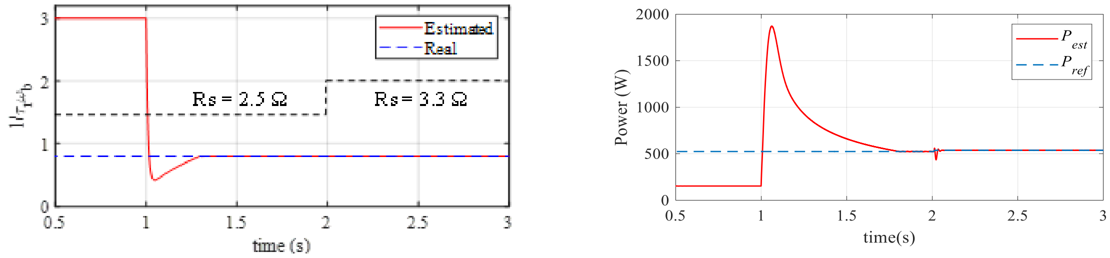
Methods	IM's rotor resistance settling time (sec.)	Robust to stator resistance variations
Proposed	0.3	Yes
[25]	2	Yes
[26]	1.5	Yes
[9]	2	Yes

3. RESULTS AND DISCUSSION

3.1. Simulation verifications

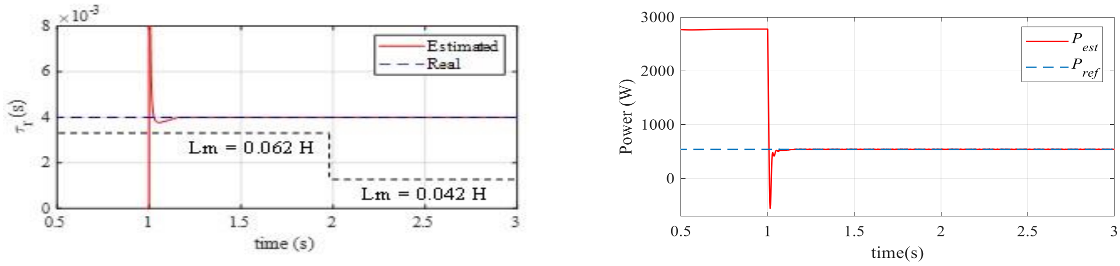
To evaluate the performance and feasibility of the proposed MRAS based IM rotor time constant value estimator by using perturbation-based ESC and active power function, simulation results using MATLAB/Simulink are presented. Table 2 presents the proposed perturbation-based ESC and the simulated IM parameters. The robustness of the proposed MRAS estimator under stator resistance variations has been investigated at Figure 4. At t=2 sec, the stator resistance has been increased by 50% as shown in Figure 4(a). This figure confirms the robustness of rotor time constant estimation against stator resistance changes. This estimation has been done under P = 530 W. The estimated and reference active powers also follow each other with no error. There is a small perturbation on estimated active power in Figure 4(b) but after very short time the estimated value converges to real one without any error. Since the perturbation-based ESC is model free approach and is not related to any information from IM model, so variations of stator resistance have no effect on robust rotor resistance identification. Figure 5, depicts the estimation results under magnetizing inductance change. The initial value of estimated $\hat{\tau}_r$ is set to zero whereas the reference value is τ_r= 0.004 s. From Figure 5(a) one can see that the estimated value converges to real one in less than 0.15 sec. At t=3 sec, the magnetizing inductance is reduced to 0.042 H. As shown in Figure 5(a) the estimated resistance follows the reference one without any error. Meanwhile, the estimated active power converges to real value without any error in Figure 5(b). The simulation results verify the robustness of proposed MRAS using perturbation-based ESC and active power.

ESC is a robust method because it is model free approach. By optimizing the cost function (error between active powers) the ESC can provide an effective control system design approach to conduct an unknown dynamic system to an equilibrium point. So, ESC always provides true estimation results regardless to model uncertainties and nonlinearities



(a) (b)

Figure 4. Robustness of rotor time constant identification: (a) rotor time constant and (b) active powers



(a) (b)

Figure 5. Rrobustness of rotor time constant estimation: (a) rotor time constant and (b) active powers

3.2. Experimental results

To evaluate the effectiveness of the new MRAS based online IM rotor time constant τ_r value estimator by using perturbation-based ESC and active power function, the 2.2 kW experimental prototype has been implemented in our research center as depicted in Figure 6. The three-phase h-bridge IGBT 2.2 kW drive has been used for FOC control of IM. It comprises six Siemens BUP314D IGBT switches, three current sensors, two voltage sensors, and the capacitor is $C = 1200\mu F$. Switching frequency of IM drive is $f_{sw} = 15kHz$. The proposed online IM rotor time constant τ_r value estimator has been implemented real-time in the PC by using MATLAB/Simulink Real Time Windows Target toolbox and the Advantech PCI-1716 data acquisition card. The DAQ PCI-1716 has been used to measure the current and voltage values and provide the estimated $\hat{\tau}_r(s)$ for IM drive. In a first case study, the initial value of $\hat{\tau}_r(s)$ is set to 60% more than real (reference) value, which is 0.004 s. Then, at $t = 1\, sec$ the proposed MRAS perturbation - based ESC estimation process is started. Figure 7 (a) presents the rotor time constant estimated value. As depicted in this figure, the estimated $\hat{\tau}_r(s)$ converges to the real (reference) value of 0.004 s in less than 0.5. As shown in Figure 7 (b), due to rotor resistance mismatch, the estimated active power is 570 W whereas the real one is 530 W. After starting of estimation process at $t = 1\, sec$ the estimated active power function is converged to the real value in less than 0.3 s. At t = 1.5 sec the estimated values of both rotor time constant and active power converge to real values with negligible errors. Based on Figures 3, since the e (= ε) converges to zero, so optimum value of rotor time constant obtained. At t = 2 sec the stator resistance is increased to 3.3 Ω (by series connection of 2.5 Ω to the motor stator windings). At this moment there is a negligible perturbation on rotor time constant estimation but after very short time the estimated value tracks the reference value in acceptable level. Since the perturbation-based ESC is model free approach and is not related to any information from IM model, so variations of stator resistance have no effect on rotor resistance identification. So, the robustness of the ESC technique to stator resistance variations confirmed by experimental results too.

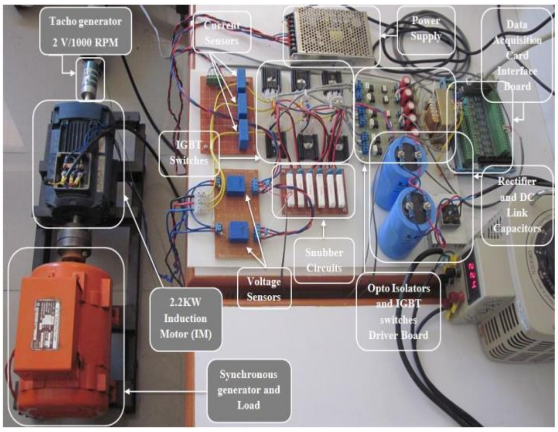
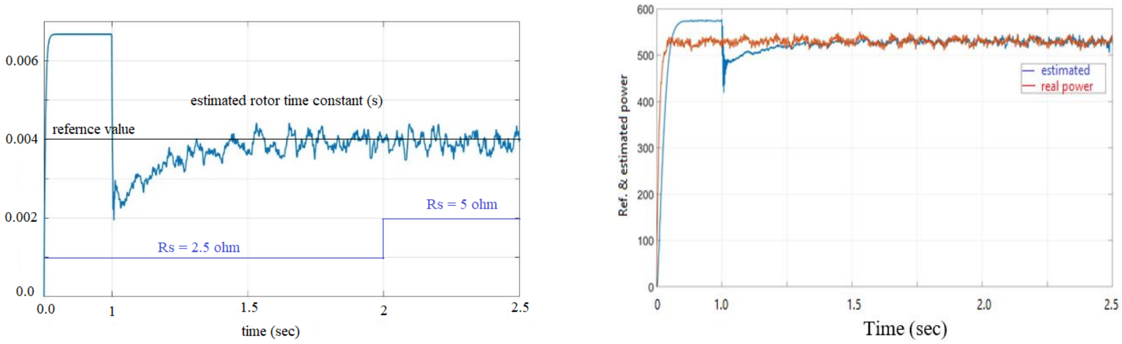


Figure 6. Experimental setup

Table 2. IM & ESC parameters

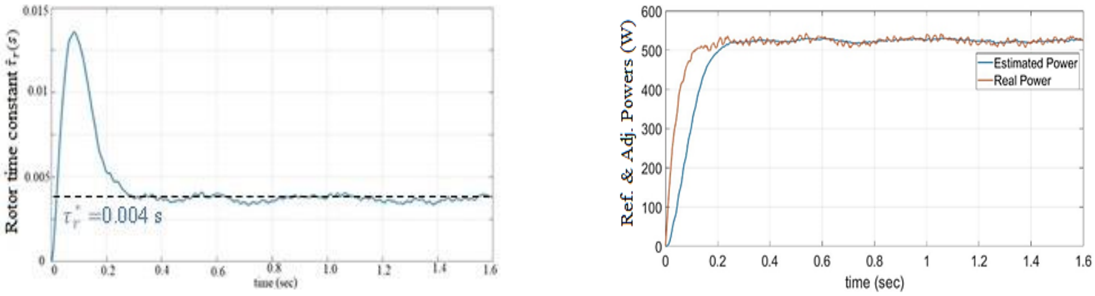
Parameters	Value
Nominal power	$P = 2200Watt$
Rated voltage	$V_{L-L} = 380V$
Number of poles	4
Nominal frequency	$f = 50Hz$
Base electrical angular frequency	$\omega_b = 2\pi \times 50\frac{rad}{sec}$
Rotor resistance	$R_2 = 3.18\Omega$
Rotor inductance	$L_2 = 0.013H$
Stator resistance	$R_1 = 2.5\Omega$
Stator inductance	$L_1 = 0.011H$
Mutual inductance	$L_m = 0.0620H$
Perturbation angular frequency	$\omega_{Perturbation} = 10000\frac{rad}{sec}$
Perturbation magnitude	$a = 0.04$
Integrator gain	$\gamma = 6$



(a) (b)

Figure 7. Experimental result: (a) rotor time constant estimation $\hat{\tau}_r(s)$ and (b) active powers

As a second case study, the initial value of $\hat{\tau}_r(s)$ for the proposed MRAS estimator is set to zero whereas the real (reference) value is 0.004 s. Figure 8(a) represents the estimated value of $\hat{\tau}_r(s)$ to converge to real value of 0.004 s in less than 0.3 sec with negligible error. Figure 8(b), illustrates the real and estimated values of the IM active power waveforms. As one can notice in this figure, the proposed active power function is converged to the real value in less than 0.25 s. By converging two active powers at t = 0.3 sec, the ε approaches to zero and based on Figures 3, estimated rotor resistance converges to real value at t = 0.3 sec. The provided experimental and simulation results verify that the proposed MRAS perturbation-based ESC and active power function are effective in the IM parameter estimation under parameter variations and can be utilized in practical applications. The similarities and match between simulation and experimental results verifies the effectiveness of the MRAS based online IM rotor time constant τ_r value estimator by using perturbation based ESC and active power function.



(a) (b)

Figure 8. Experimental result: (a) identification of $\hat{\tau}_r(s)$ and (b) active powers

4. CONCLUSION

A new MRAS based IM rotor time constant estimator by utilizing the perturbation based ESC method and modified active power function was proposed in this research work. The four major advantages of the proposed estimator for IM rotor time constant are; It is robust to any noise from switching devices, as both the adjustable and reference models have the same equation and the same inputs, and thereby the noise will be cancelled out by MRAS comparator. The proposed perturbation based ESC for MRAS mechanism is able to estimate IM rotor resistance under a wide range variations. The rotor resistance estimation is robust to any variations of stator resistance, magnetizing inductance, and induction motor load. Application of ESC for IM parameter estimations. These advantages are achieved because the ESC is robust to IM parameter variations and model uncertainties. The comparison results verify that the ESC method provides faster rotor identification process compared to other methods. The provided experimental results verify that the proposed ESC-based method effective and can be applied in practical applications.

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