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Novel Unified Control Method of Induction and Permanent Magnet Synchronous Motors

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ABSTRACT

Many control schemes have been proposed for induction motor and permanent magnet synchronous motor control, which are almost highly complex and non-linear. Also, a simple and efficient method for unified control of the electric moto are rarely investigated. In this paper, a novel control method based on rotor flux orientation is proposed. The novelties of proposed method are elimination of q-axis current loop (one controller is omitted) and utilization of a new dynamic current rate limiter. Also, unlike the conventional methods, the proposed control method could be applied on both induction motor and permanent magnet synchronous motor with only minor modifications. In addition to mentioned advantages, the torque ripple and current harmonic is reduced, too. Theoretical survey and simulation results clearly show the capability of proposed method for high and low speed applications in steady and transient states.

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NOMENCLATURE

v_{sd}	d axis component of stator voltage	R_s	Stator resistance
v_{sq}	q axis component of stator voltage	R_r	Rotor resistance
λ_{sd}	d axis component of stator flux	λ_{pm}	Permanent magnet flux
λ_{sq}	q axis component of stator flux	ω_e	Synchronous speed
λ_{rd}	d axis component of rotor flux	ω_{sl}	Slip speed
λ_{rq}	q axis component of rotor flux	ω_m	Electrical speed of rotor
i_{sd}	d axis component of stator current	ω_{mech}	Mechanical speed of rotor
i_{sq}	q axis component of stator current	P	Pole number
i_{rd}	d axis component of rotor current	T_e	Electromagnetic torque
i_{rq}	q axis component of rotor current	T_L	Load torque
L_s	Stator inductance	J	Inertia
L_r	Rotor inductance	B	Firiction coefficient
L_m	Mutual inductance		

1. INTRODUCTION

Electric motors are used nearly for a century. According to the type of power supply, electric motors are classified into DC and AC motors. Both of motors are utilized to drive mechanical loads in varying speeds. Therefore, variable speed drives have been introduced in previous decades [1]. In 1896, an efficient way has been proposed to control speed of DC motors by controlling armature voltage and keeping excitation current in constant mode.

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However, nowadays, AC motors are preferred in the industrial environments [1, 2]. The reasons are laid behind AC motors advantages over DC motors. Therefore, various speed control methods have been presented. In general form, AC motor control methods are categorized into scalar and vector controls. In the scalar control, amplitude and frequency of supplied voltage (or current) are modified. Also, the control is based on the steady state equation of the motor. The superiority of scalar control is its simplicity. However, if precise control is expected, the vector control should be utilized. In 1969, field oriented control method (FOC) has been suggested. FOC method was based on the separated control of flux component and torque component currents. FOC method has been classified into three groups, which are named direct rotor flux oriented control (DRFOC), indirect rotor flux oriented control (IRFOC), and stator flux oriented control (SFOC) [3].

The difference between DRFOC and IRFOC is based on the synchronously rotating reference frame angle. In DRFOC, voltage and current sensors are used to estimate $\alpha\beta$ component of the rotor flux. Then, according to the estimated values, synchronous angle has been obtained. In the other hand, for IRFOC, the estimated value of slip speed for induction motor (IM) and measured (or estimated) value of rotor speed are summed to calculate the angle. According to the procedure of DRFOC and IRFOC, rotor flux and torque of the motor have been controlled separately. Therefore, the control of AC machine became as simple as DC machine. However, in SFOC the torque producing and flux producing component of stator currents have not been decoupled. Therefore, complex and time-consuming computation should be performed.

According to the explanation and numerous references, in previous decades, various control methods have been proposed for AC motors. Also, in order to improve the performance of the classical control methods, various papers have been published [4-9]. Specially, model perdictive and sliding mode control are investigated [10- 12].

As it was explained in first paragraph, the AC motors are first choice in the industrial applications [2, 13]. Also, the popular types of AC motor are induction motor and permanent magnet synchronous motor (PMSM). IM and PMSM have almost same stator construction. Therefore, dynamic equations of stator have same forms. However, in terms of rotor structure, they are completely different from each other. The main issue in the controlling of AC motors, is torque or speed control. Generally, the motors that produce torque in uniform way have common features that provide unified control capability [14]. Also, the hardware of control system is common for IM and PMSM. Therefore, according to the description, a controller which can handle both types of AC drives could be an industry-specific suggestion.

This type of controller is called unified or universal controller. In other words, the unified control is type of drive system that can be utilized with the least modification on different types of motor (IM and PMSM).

It should be noted that, the most user of AC motors in the industry are whom do not have the detailed information about motor performance and its control methods. In other words, if the motor type was changed for any reasons, the control system must be replaced. This issue may cause several problems in the process of using the AC motors, which including an increase in installation cost, training the user to use controller for various motors, time-consuming repairs, and etc. Thus, the use of a unified control system, which can drive the AC motors, is cost effective. It should be noted that, if the goal of control is to optimize AC motor performance in all aspects, it’s more appropriate to have unique controller based on the exact model of that motor. In other words, comparison between the output results of unified controlled motor and specifically optimized controlled motor are not reasonable.

So far, the papers about unification have been classified into three perspectives: 1) from the viewpoint of performance, 2) from the viewpoint of modeling, and 3) from the viewpoint of control method.

In the following, a review of the references available in each of these perspectives are presented. Performance unification is referred to unification of steady state and transient state control procedure. Only a few investigation have been conducted around performance unification. In order to unify the performance control of AC motors in transient and steady states, a method called the spiral vector theory is presented [15-17]. The spiral vector is a time-variant exponential function with complex index.

In the view point of modeling several papers have been investigated. The starting point of choosing proper control method for AC motor is to choose the acceptable model of the motor. A new model for induction and synchronous motor is presented taking into account iron losses [18]. In order to achieve a unified model, a motor with a rotor including permanent magnet and squirrel cage can be considered [19]. It has been reported [19], a unified off-line method was also used to measure machine parameters. A generic and unified model for induction, reluctance, permanent magnet, surface-mounted PMSM (SPMSM), interior-PMSM (IPMSM), and wound rotor synchronous motor is presented [20]. Thus, by modifying the mentioned model, a specific AC motor model could be attained. In A new concept of model unifying is presented in literature [21, 22]. Active flux (AF) or torque producing flux makes it possible to model and control the salient pole motors as simple as the non-salient ones [21]. Also, an equivalent flux concept is presented in literature [22], which is almost the same as AF. A general mode observer for sensor-less control of AC motors can be used [21, 22]. A unified flux estimator and vector control is introduced for IM and SPMSM [23]. Inverse Γ equivalent circuit of IM is modified to obtain a similar schematic for SPMSM. Afterwards, according to the similarities of IM and SPMSM, the estimation of the rotor position of the SPMSM is similar to estimation of the rotor flux position of IM.

The common control methods are tried to be unified in the view point of control unification. In general, direct torque control (DTC) and FOC methods are analogous to each other [24]. As it is stated in literature [24], in order to obtain a fast torque change, rotational emf (is produced due to the rotation of magnetic field) and pulsational emf (is produced due to magnitude change of magnetic field) should be maximized and minimized, respectively. This procedure is achieved for DTC and FOC in different ways. In other words, unlike common belief, DTC and FOC are mostly related to each other [24]. As the dynamic equations of motor could be written in different reference frames, the vector control unification for the induction motor from the perspective of different reference frames (rotor flux, stator flux, and air-gap flux) is investigated by Lai [25]. In other words, it has been shown that, vector control in different reference frames does not change hardware of induction motor control system. The only minor effect is the change of software in the controller.

In order to provide universal control, it has been tried to use estimators that could be applied with minimal variation for all types of AC motors [26]. Also, the presented control method (which can be DTC, FOC, and scaler control) selects the estimator according to the type of AC motor. Finally, based on the output of the estimators and the reference values, the optimal control is implemented on the AC motor.

A unified direct-flux vector control for AC motors (including IM, synchronous reluctance, and PMSM) is presented in literature [27]. The main point in this method is that the d-axis of reference frame is considered to be aligned with the stator flux. As a result of this assumption, the stator flux and the torque are controlled by the component of the stator voltage and component of stator current, respectively. In this control method, the only difference between the controls of AC motors is referred to estimation of flux in low speeds.

In this paper, the novel unified control method is introduced for IM and PMSM. In order to validate the proposed method a mathematical study is presented. The proposed method is as precise as FOC, however, it uses less component than FOC. Also, except the starting moment, the response time of the proposed method is faster than that of the conventional methods. In addition to the mentioned advantages, the proposed method represents better current response. Therefore, simplicity, accuracy, and applicable response are the main features of the proposed method.

This paper is organized as follows. In section 2, dynamic model of IM and PMSM is presented. Then, according to the section 2, the unified model is extracted in section 3. Section 4 is about theoretical study of the FOC and the proposed control method. Also, the dynamic current limiter is proposed in section 4. The simulation results are expressed in section 5. Finally, the conclusion is presented in section 6.

2. DYNAMIC MODEL OF IM AND PMSM

The dynamic equations of stator and rotor voltage (voltage- current equations) in the synchronous reference frame for IM could be written as follows [22, 25]:

$$v_{sq} = R_s i_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_e \lambda_{sd} \tag{1}$$

$$v_{sd} = R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_e \lambda_{sq} \tag{2}$$

$$0 = R_r i_{rq} + \frac{d\lambda_{rq}}{dt} + \omega_{sl} \lambda_{rd} \tag{3}$$

$$0 = R_r i_{rd} + \frac{d\lambda_{rd}}{dt} - \omega_{sl} \lambda_{rq} \tag{4}$$

Also, the flux- current equations of IM can be expressed as follows:

$$\lambda_{sq} = L_s i_{sq} + L_m i_{rq} \tag{5}$$

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd} \tag{6}$$

$$\lambda_{rq} = L_r i_{rq} + L_m i_{sq} \tag{7}$$

$$\lambda_{rd} = L_r i_{rd} + L_m i_{sd} \tag{8}$$

If IRFOC method is applied to IM [2], the resultant and simplified voltage- current equations can be obtained as follows:

$$\begin{aligned} v_{sq} &= (R_s + R_r \frac{L_m^2}{L_r^2}) i_{sq} + \sigma L_s \frac{di_{sq}}{dt} \\ &\quad + \omega_m \frac{L_m}{L_r} \lambda_{rd} + \omega_e \sigma L_s i_{sd} \end{aligned} \tag{9}$$

$$\begin{aligned} v_{sd} &= (R_s + R_r \frac{L_m^2}{L_r^2}) i_{sd} + \sigma L_s \frac{di_{sd}}{dt} \\ &\quad - R_r \frac{L_m}{L_r^2} \lambda_{rd} - \omega_e \sigma L_s i_{sq} \end{aligned} \tag{10}$$

In Equations (9) and (10), σ and ω_m can be written as follows:

$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r} \tag{11}$$

$$\omega_m = \omega_e - \omega_{sl} \tag{12}$$

The dynamic equations of stator voltage in the synchronous reference frame for PMSM is exactly the same as Equations (1) and (2). However, the flux- current equations is quite different and could be expressed as follows [22]:

$$\lambda_{sq} = L_s i_{sq} \tag{13}$$

$$\lambda_{sd} = L_s i_{sd} + \lambda_{pm} \tag{14}$$

As it is clear, in the PMSM, rotor rotates in synchronous speed. Also, rotor equivalent resistance is zero. According to the PMSM conditions, substituting Equations (13) and (14) into Equations (1) and (2), yield [28]:

$$v_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + \omega_e \lambda_{pm} + \omega_e L_s i_{sd} \tag{15}$$

$$v_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega_e L_s i_{sq} \tag{16}$$

Torque equation for IM and PMSM can be considered as follows:

$$T_e = \frac{3}{2} \times \frac{P}{2} \left(\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd} \right) \tag{17}$$

Of course, Equation (17) can be altered, according to the types of motor and the required issues, to the different forms. Finally, the mechanical dynamic equation of motor (IM and PMSM) is as written below.

$$T_e - T_L = J \frac{d\omega_{mech}}{dt} + B\omega_{mech} \tag{18}$$

$$\omega_m = \frac{P}{2} \omega_{mech} \tag{19}$$

3. UNIFIED MODEL OF IM AND PMSM

According to Equations (9), (10), (15), and (16), it is clear that from a stator perspective, a similar model can be considered for IM and PMSM. This unique model is introduced as a unified model as follows:

$$v_{sq} = R_{eq} i_{sq} + L_{eq} \frac{di_{sq}}{dt} + v_Q \tag{20}$$

$$v_{sd} = R_{eq} i_{sd} + L_{eq} \frac{di_{sd}}{dt} + v_D \tag{21}$$

Considering Equations (9) and (10), the parameter values of unified model for IM are as follows:

$$R_{eq} = R_s + R_r \frac{{L_m}^2}{{L_r}^2} \tag{22}$$

$$L_{eq} = \sigma L_s \tag{23}$$

$$v_Q = \omega_m \frac{L_m}{L_r} \lambda_{rd} + \omega_e \sigma L_s i_{sd} \tag{24}$$

$$v_D = -R_r \frac{L_m}{L_r^2} \lambda_{rd} - \omega_e \sigma L_s i_{sq} \tag{25}$$

If $R_r = 0$, $\omega_m = \omega_e$, and $\frac{L_m}{L_r} \lambda_{rd} = \lambda_{pm}$ are considered, the parameter values of the unified model for PMSM are obtained.

$$R_{eq} = R_s \tag{26}$$

$$L_{eq} = L_s \tag{27}$$

$$v_Q = \omega_e \lambda_{pm} + \omega_e L_s i_{sd} \tag{28}$$

$$v_D = -\omega_e L_s i_{sq} \tag{29}$$

According to Equation (17) and principal of FOC method, electromagnetic torque for IM and PMSM, can be written as follows:

$$T_e = \frac{3}{2} \times \frac{P}{2} \lambda_R i_{sq} \tag{30}$$

λ_R is equivalent flux of rotor. For PMSM, λ_R is same as λ_{pm}, and for IM it is equal to $\frac{L_m}{L_r} \lambda_{rd}$. Equations (20), (21), and (30) clearly show that despite the fundamental differences between IM and PMSM, one can provide a unified model and control method.

4. PROPOSED CONTROL METHOD

In order to illustrate the proposed control method, accurate investigation on FOC method is needed. Figure 1 shows the FOC with the cascade control method. As it is evident, primary and secondary objectives are defined in the cascade control method. The primary purpose is to control the speed (or position) of AC motor, which is achieved by the required voltage injection. But the second goal is to adjust flow of current in AC motor windings. In other words, according to the applied load, the current is adjusted so that, in addition to fulfill its working condition, it does not exceed the permissible limits.

In the most cascade control systems, proportional-integral (PI) controllers are used. The reason for this is related to the time constants of the primary and secondary systems (primary and secondary goals). In other words, the response time of the speed is much larger than that of current.

Therefore, for each of the primary and secondary systems, a PI controller can be designed, individually.

As shown in Figure 1, in the conventional FOC, two PI controllers are used to control d and q axes currents in the inner loops. Also, another PI controller is used for controlling the speed in the outer loop. As a result, at least, three feedback signals (ω_m, i_{sd}, and i_{sq}) should be provided. Several methods were surveyed to obtain feedback signals. The simplest and most expensive way is the use of at least two current sensors and a speed sensor.

Also, three reference signals (ω_m^*, i_{sd}^*, and i_{sq}^*) should be determined. ω_m^* is a user defined signal and i_{sd}^* is function of speed and motor rated parameters. However, i_{sq}^* is obtained according to the applied mechanical load. As a result and according to Equation (30), it can be calculated as follows:

$$i_{sq}^* = \frac{T_e^*}{\frac{3}{2}\times\frac{P}{2}\times\lambda_R} \tag{31}$$

Therefore, in order to control the torque, q axis current should be modified. According to Equations (24), (25), (28), and (29), the unified model have non-linear parts, therefore input-output linearization method is used. To do this, $v_{sq}-v_Q$ and $v_{sd}-v_D$ are defined as new variables. The open loop transfer function of inner loops (d and q axes) are written as follows:

$$\frac{I_{sq}}{V_{sq}-V_Q} = \frac{\frac{1}{L_{eq}}}{S+\frac{R_{eq}}{L_{eq}}} \tag{32}$$

$$\frac{I_{sd}}{V_{sd}-V_D} = \frac{\frac{1}{L_{eq}}}{S+\frac{R_{eq}}{L_{eq}}} \tag{33}$$

According to Equations (32) and (33), two PI controllers can be designed for d and q axes. The methodology of input-output linearization for d and q axes by use of PI controllers are shown in Figure 2. K_{inv} is constant and is used to model the inverter in the simplest method. There are various methods for determining k_I and k_p. In this paper, pole assignment method is considered. In the mentioned technique, the actual closed-loop polynominal is parameterized utilizing the unkonwn PI controller parameters. Then, it is made to be equal to a desired closed-loop polynominal of the same order. At last, the values that were calculated by the mentioned method, could be modified to obtain more proper responses.

Figure 3 shows the speed control loop for unified model. The transfer function of outer loop is achievable according to Equations (18), (30), and Figure 3. According to Equation (18), the load torque should be present in Equation (34). However, when a mechanical load is applied to an electric motor, control system treats it as disturbance. In other words, tries to reach new stability region by changing state variables. As a result, when the system reaches to a stable point, the load torque will be rejected.

$$\frac{\Omega_{mech}}{I_{sq}} = \frac{\frac{3}{2}\times\frac{P}{2}\times\frac{\lambda_R}{J}}{S+\frac{B}{J}} \tag{34}$$

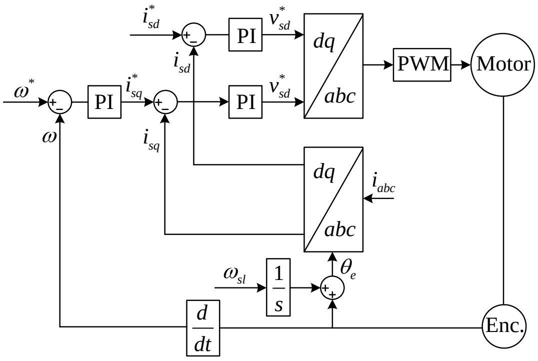
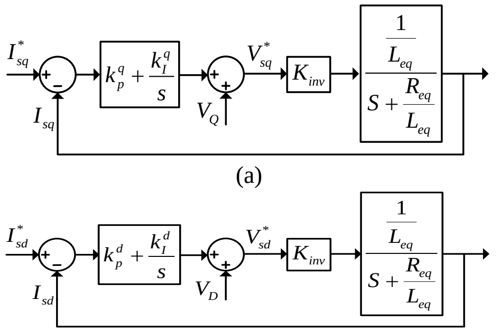


Figure 1. Schematic of conventional FOC



(a)

(b)

Figure 2. The inner loop of current controller with input-output linearization for: (a) q axis and (b) d axis

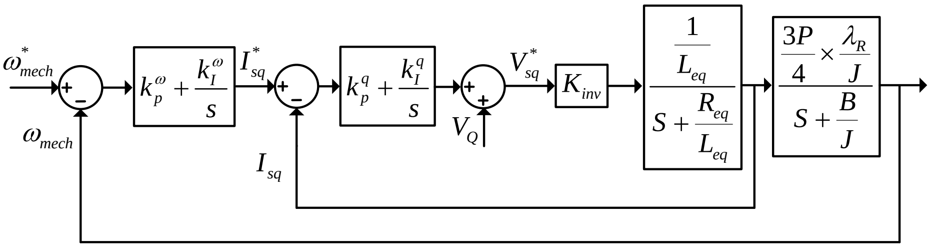


Figure 3. Speed control loop for unified model of motor in FOC

According to Figure 3 and Equation (34), Ω_{mech} and I_{sq} are output and input parameters, respectively. However, in order to control ω_{mech}, i_{sq} is not accessible choice. Therefore, i_{sq}^{*} is chosen and according to Figure 3 and Equation (34), a new open loop transfer function is obtained.

$$\frac{\Omega_{mech}}{I_{sq}^{*}}=\frac{\frac{3}{2}\times\frac{P}{2}\times\frac{\lambda_R}{J}}{S+\frac{B}{J}}\times\frac{(2\zeta\omega_n S+\frac{R_{eq}}{L_{eq}})+\omega_n^2}{S^2+2\zeta\omega_n S+\omega_n^2} \tag{35}$$

According to Figure 3 and Equation (35), k_p^q and k_I^q are considered as follows:

$$k_I^{q}=\frac{L_{eq}\omega_n^2}{K_{inv}} \tag{36}$$

$$k_p^{q}=\frac{2\zeta\omega_n L_{eq}-R_{eq}}{K_{inv}} \tag{37}$$

Equation (35) shows a third order transfer function. The three poles of Equation (35) can be written as $S_1=-\frac{B}{J}$ and $S_{1,2}=-\zeta\omega_n\pm j\,\omega_n\sqrt{1-\zeta^2}$. Hence, PI controller is not appropriate choice for speed control loop. However, if $\zeta\omega_n$ is chosen sufficiently larger than $\frac{B}{J}$, Equation (35) would be approximated as the first order transfer function. As a result, the PI controller can be used in Figure 3.

Unlike the FOC method, which uses the so-called cascade method to control motor and generate reference signals, the proposed method uses two loops to generate the reference voltage of d and q axes (v_{ds}^{*} and v_{sq}^{*}). In other words, primary and secondary control purpose of FOC is reduced to one goal. In the proposed method, according to Equation (33) and Figure 2b, v_{sd}^{*} is generated. Also, same as the FOC method, i_{sd}^{*} is considered based on the speed and parameters of motor.

However, the main difference between the proposed and FCO method is how to obtain v_{sq}^{*} . According to Equations (32) and (34), it is possible to obtain speed-voltage transfer function in q axis, which can be written as follows.

$$\frac{\Omega_{mech}}{V_{sq}-V_Q}=\frac{\frac{3}{2}\times\frac{P}{2}\times\frac{\lambda_R}{J}\times\frac{1}{L_{eq}}\times K_{inv}}{(S+\frac{B}{J})(S+\frac{R_{eq}}{L_{eq}})} \tag{38}$$

The speed- voltage transfer function Equation (35) is in second order. Therefore, proportional-integral-deravetive (PID) controller should be chosen. However, the careful survey reveals that in the motors the electrical pole ($S_e=-\frac{R_{eq}}{L_{eq}}$) is much larger than mechanical pole ($S_m=-\frac{B}{J}$). In other words, S_m is the dominant pole. Therefore, Equation (38) can be simplified as follows:

$$\frac{\Omega_{mech}}{V_{sq}-V_Q}=\frac{\frac{3}{2}\times\frac{P}{2}\times\frac{\lambda_R}{J}\times\frac{1}{R_{eq}}\times K_{inv}}{(S+\frac{B}{J})} \tag{39}$$

According to Equation (39), a PI controller will be used in the proposed control method. Figure 4 shows the proposed control method for q axis. Figures 3 and 4 show the main difference between the conventional and proposed method. According to the explanations, omitting a PI controller in the proposed method cause considerable simplification in motor control. Also, i_{sq} will not be used as a feedback signal. However, due to elimination of the feedback loop of i_{sq}, the current rise would be occurred during startup and mechanical load change. Therefore, a novel dynamic current rate limiter is proposed.

Figure 5 shows the flowchart of the proposed limiter. The mechanism of the limiter is simple as explained in the following:

The value of $a=\frac{\omega^*-\omega}{\omega^*}$ subsequently is compared with 0.9, 0.8, … and 0.3. Then, considering the value of a, $\omega^*-\omega$ (which is the input of the PI controller) is multiplied by stepwise-increasing factor. It lasts until the value of a reaches to less than 0.3. Therefore, proper reference voltage (and then current) would be generated in the mentioned moments and current limitation would be accomplished.

Unlike the conventional FOC, the unified model of electric motor is utilized in the proposed method. Hence, the mentioned difficulties in the introduction could be solved. In other words, there is no need to change or modify the controller device and the implemented control program, due to the changing of motor type. Therefore, considerable cost save in installation, maintenance, and operator training would be accessible. This is due to the utilization of a single driver for both IM and PMSM control.

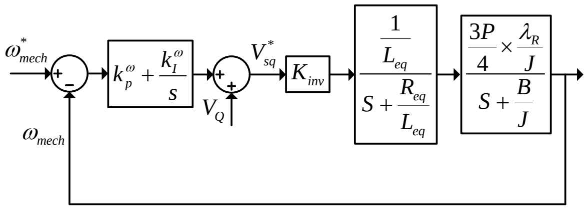


Figure 4. Speed control loop for unified model of motor in the proposed control method

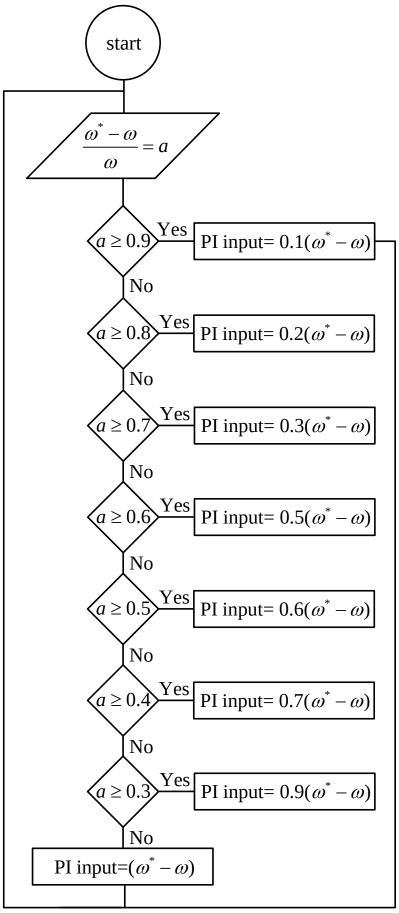


Figure 5. Flowchart of dynamic current rate limiter

5. SIMULATION RESULTS

In order to verify the performance of the proposed unified control method, various simulations has been done in the Matlab simulink software. Simulations were based on a 1.1 kW, 380 V, 50 Hz, Y connected IM and a 0.4 kW, 380 V PMSM (parameters are listed in Tables 1 and 2, respectively). Also, the PI controllers coefficients for the FOC and proposed method are tabulated in Tables 3 and 4.

Figure 6 shows the configuration of the proposed control method which is applied to IM and PMSM.

TABLE 1. Parameters of IM

Parameter	Value
Rated power	1.1 kW
Rated torque	11.2 N.m
Rated voltage	380 V
Rated current (rms)	3.3 A
Rated frequency	50 Hz
Rated speed	910 rpm
Stator resistance	5.72 Ω
Stator leakage inductance	6.6 mH
Rotor resistance	5.3 Ω
Rotor leakage inductance	6.6 mH
Magnetizing inductance	0.25 H
Rotor inertia	0.0054 kg.m^2
Friction coefficient	0.00021 kg.m^2/s
Number of pole pairs	6

TABLE 2. Parameters of PMSM

Parameter	Value
Rated power	0.4 kW
Rated torque	1.3 N.m
Rated voltage	380 V
Rated current (rms)	2.5 A
Rated speed	3000 rpm
Stator resistance	0.9 Ω
Stator inductance	5.9 mH
PM flux	0.0933 Wb
Rotor inertia	0.62×10^{-4} kg.m^2
Friction coefficient	3.183×10^{-4} kg.m^2/s
Number of pole pairs	8

The needed voltage vectors are generated with SVM method by 5 kHz switching frequency.

Also the DC voltage source which is connected to the inverter is chosen to be 550 V. In the following, various conditions for speed reference are supposed and diverse results are explained.

In spite of various simulation, only part of the results could be presented here. It is necessary to note that, the PI controller of both the FOC and the proposed method are designed to obtain two objectives. Firstly, as rapid as possible response time for speed to be achieved. Secondly, the current response should be remained in the permissible range.

5. 1. Low Speed Performance

In order to verify the capability of the proposed control method in the low speed operation, the step reference signal with 6% magnitude of rated speed in no load condition is applied to the controller at t=0.1s. The 6% of the rated speed for PMSM and IM is $6\,\mathrm{rad/s}$ and $19\,\mathrm{rad/s}$, respectively. This condition is maintained until t=0.5s. Then, 25% of rated load is applied to the shaft of motor (0.325N.m for PMSM and 2.8N.m for IM). Figure 7 shows rotor speed responses for mentioned condition in PMSM and IM, respectively. Also, Figures 9 and 10 represent the diagrams of the torque and the current in the aforementioned case.

It is evident that, both of the FOC and the proposed method are applicable in the low speed operation. The evaluation of Figure 7 could be divided into start up, load change, and steady state moments. For PMSM, the proposed method has faster dynamic than FOC (0.3s) in the load change moment. However, the FOC has 0.02s faster response in the startup. For IM, the startup dynamic is similar for the both methods. Also, FOC has 0.08s faster dynamic in load change moment. However, considerable disturbance could be observed in the speed response of the FOC. In other words, the proposed method has more stable dynamic than the FOC. As it is shown in Figure 8, accuracy and dynamic of the proposed method and the FOC are similar.

However, in the proposed method, current increment is smoother. In other words, the growth of the current in the FOC is sharp. Also, it is clear that, for the IM the total harmonic distortion (THD) of the current in the FOC is more than the proposed method. At the moment of load change, both of the FOC and the proposed method control the system acceptably. In Figure 9, generally, both methods have analogous response for PMSM. However, the response of the proposed method for IM has less torque ripple than the FOC, which can cause considerable advantages.

TABLE 3. Coefficient of the PI controller in the FOC

Coefficient	IM	PMSM
k_p^{ω}	1	0.062
k_I^{ω}	25	0.3183
k_p^{q}	25	51
k_I^{q}	1025	8645
k_p^{d}	50	67
k_I^{d}	600	9012

TABLE 4. Coefficient of the PI controller in the proposed method

Coefficient	IM	PMSM
k_p^{ω}	3	0.0003
k_I^{ω}	50	20.37
k_p^{d}	0.1	5
k_I^{d}	1000	5000

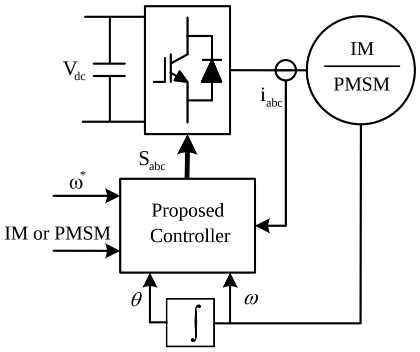
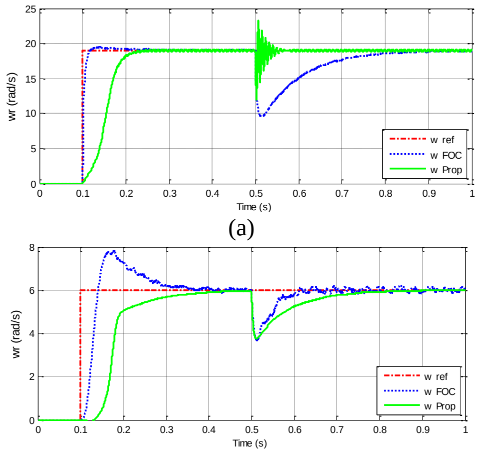


Figure 6. Configuration of proposed unified control method

5. 2. Dynamic Behavior

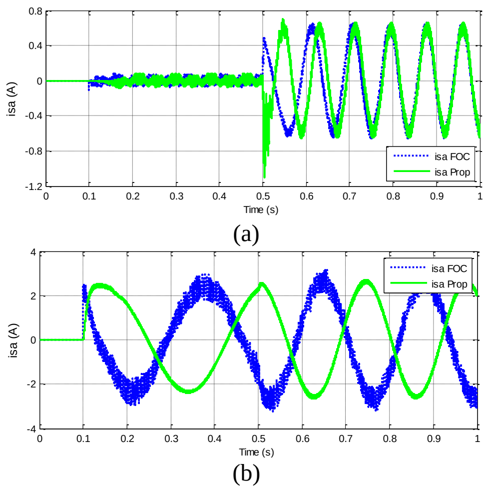
To evaluate the torque disturbance rejection capability in full load operation, the multistep simulation (for speed and load torque) is



(a)

(b)

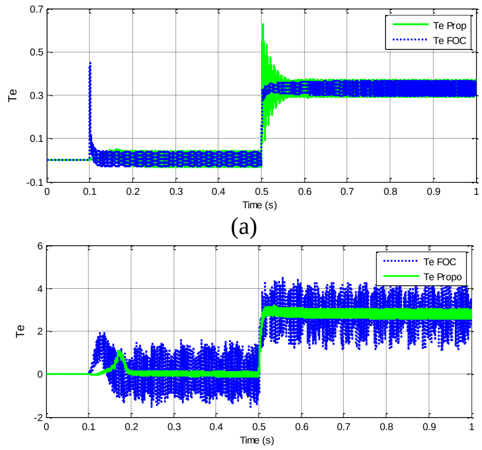
Figure 7. Speed response in 6% rated speed for (a) PMSM (b) IM



(a)

(b)

Figure 8. Current variation for low speed operation (a) PMSM (b) IM



(a)

(b)

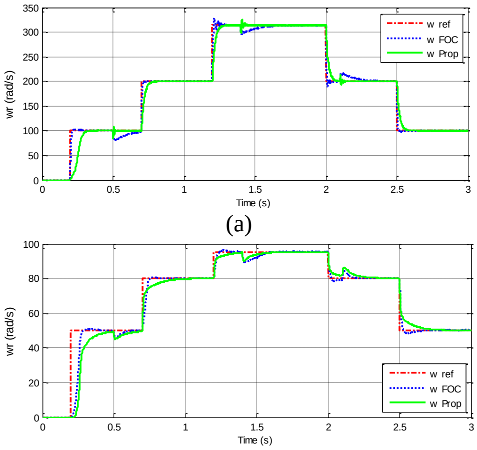
Figure 9. Torque variation for low speed operation (a) PMSM (b) IM

applied to the considered system. For PMSM reference speed of 100, 200, 314, 200, and 100 rad/s is applied at t=0.2, 0.7, 1.2, 2, and 2.5s, respectively.

Also, step load torque of 0.7, 1.3, and 0.7N.m is applied at t=0.5, 1.4, and 2.1s. On the other hand, for IM at aforementioned times 50, 80, 95, 80, and 50 rad/s for reference speed is considered. Also, the load torque of 5, 11.2, and 5N.m is applied to the motor in above mentioned times. Figures 10, 11, and 12 represent the speed response, stator current variation, and torque response, respectively.

Comparison between speed response of the proposed method and the FOC for IM and PMSM in Figure 10 reveal that the proposed method has acceptable performance in rated speed operations, too.

Due to the usage of dynamic current limiter in the proposed method, the FOC has faster speed response at the start up moment in PMSM.



(a)

(b)

Figure 10. Speed response in multistep reference speed for (a) PMSM (b) IM

However, one can optimize the operation of dynamic limiter in order to achieve rapid speed response for the proposed method which is not in the scope of the paper. However, as it was mentioned before, the proposed method has faster dynamic at the load change moments.

In spite of the slower speed response for the proposed method at the startup, according to Figure 11, the aforementioned limiter controls the current in safer manner. In other words, less current stress would be on the stator windings.

Also, less current THD would be present in the proposed method. It is clear that, less THD and accurate responses show privileges of the proposed control method.

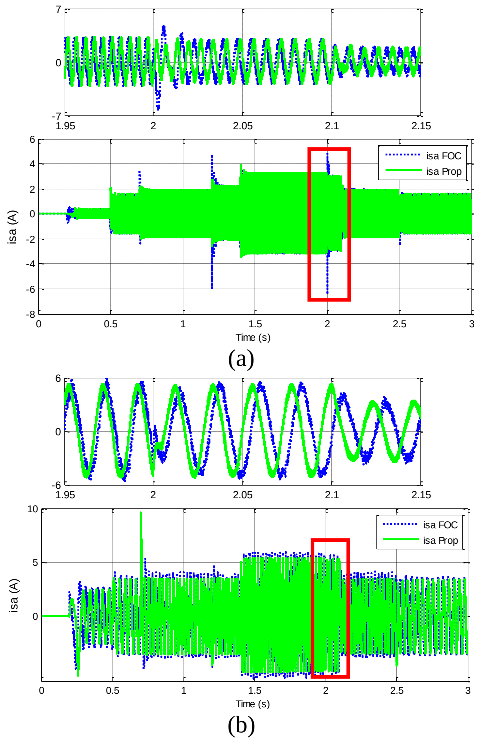
In other words, the torque response of the proposed method is as acceptable as the FOC. However, as it was mentioned before, less torque ripple is the advantage of the proposed method.

5. 3. Effect of Stator Resistance Variation

Ordinarily, stator resistance variation has considerable effect on the performance of the most of the control schemes. Therefore, various methods have been proposed to mitigate the mentioned effect. It is clear that, R_s variation has considerable effect in the low speed operation [29, 30]. In order to show the robustness of the proposed method against the R_s variation, the low speed operations are simulated for different conditions. The multi-step speed reference signal is applied to the controller with the following characteristic:

$$\begin{cases} t=0.2s \ \ to \ \ t=1.5s\,, \ \omega_{IM}^{*}=10\,, \ \omega_{PMSM}^{*}=19 \\ t=1.5s \ \ to \ \ t=2.5s\,, \ \omega_{IM}^{*}=6\,, \ \omega_{PMSM}^{*}=10 \\ t=2.5s \ \ to \ \ t=3.5s\,, \ \omega_{IM}^{*}=0\,, \ \omega_{PMSM}^{*}=0 \\ t=3.5s \ \ to \ \ t=4.5s\,, \ \omega_{IM}^{*}=6\,, \ \omega_{PMSM}^{*}=10 \\ t=4.5s \ \ to \ \ t=6s\,, \ \omega_{IM}^{*}=10\,, \ \omega_{PMSM}^{*}=19 \end{cases}$$

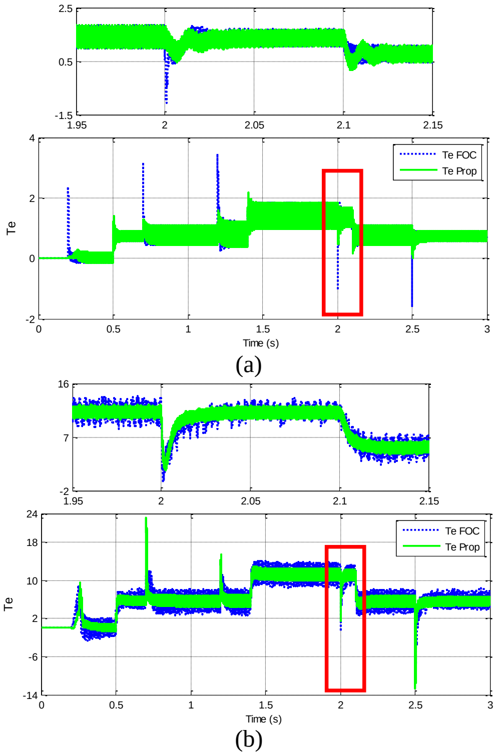
Also, 25% of the nominal load torque is applied to the shaft of rotor at $t=1s$ (in the loaded condition).



(a)

(b)

Figure 11. Current variation when multistep reference speed and load torque is applied to (a) PMSM (b) IM

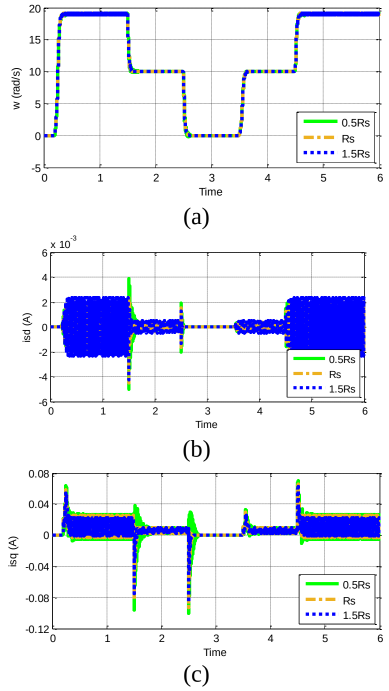


(a)

(b)

Figure 12. Torque variation when multistep reference speed and load torque is applied to (a) PMSM (b) IM

The simulation has been conducted for stator resistance value of R_s, $0.5R_s$, and $1.5R_s$. Figures 13 and 14 represent the effect of stator resistance variation in PMSM when the proposed method is applied.

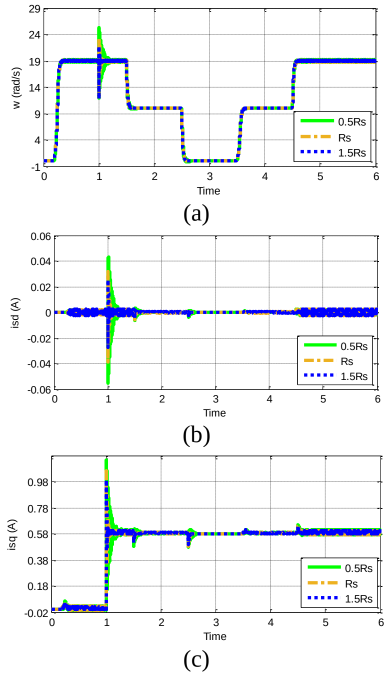


(a)

(b)

(c)

Figure 13. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for PMSM in no load condition (proposed method)



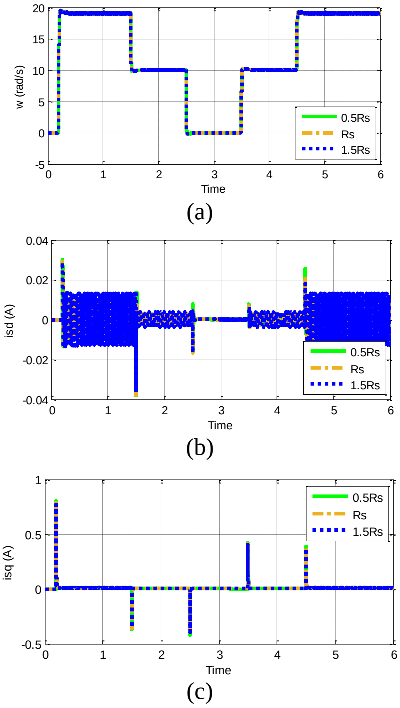
(a)

(b)

(c)

Figure 14. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for PMSM in 25% loaded condition (proposed method)

Also, Figures 15 and 16 shows the same results for the FOC method.



(a)

(b)

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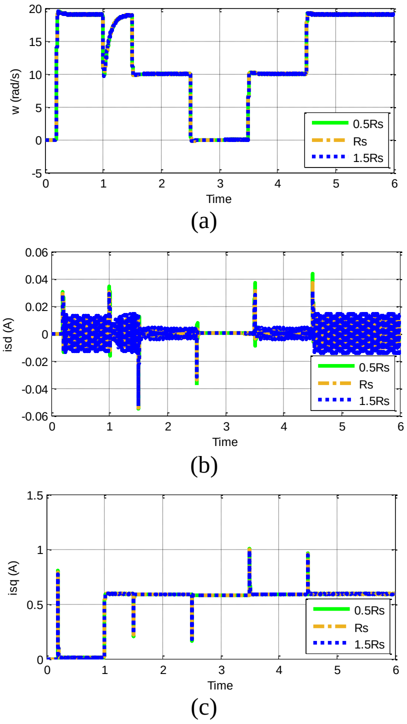
Figure 15. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for PMSM in no load condition (FOC method)



(a)

(b)

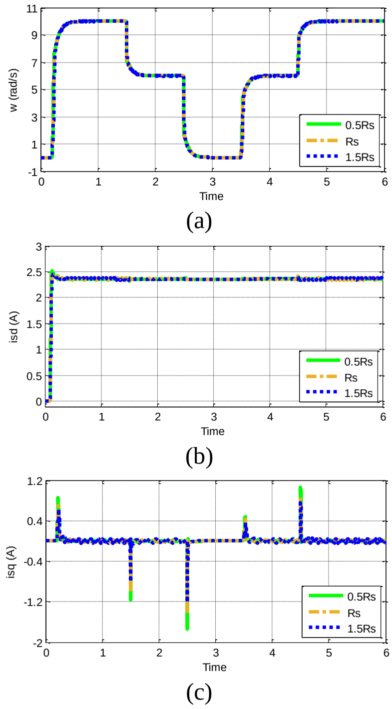
(c)

Figure 16. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for PMSM in 25% loaded condition (FOC method)

According to Figures 13, 14, 15 and 16, alteration of R_s has minor effect on the mechanical and electrical response of motor. In other words, the proposed method is as robust as the FOC method when R_s varies.

Figures 17 and 18 show the response of IM when the proposed and the FOC methods are applied in the no load condition, respectively. Also, Figures 19 and 20 are representing the aformentioned states for loaded condition.

As it is clear, the only minor differences for electrical and mechanical parameters are existed (for three mentioned condition), which cannot be distinguished with each other.



(a)

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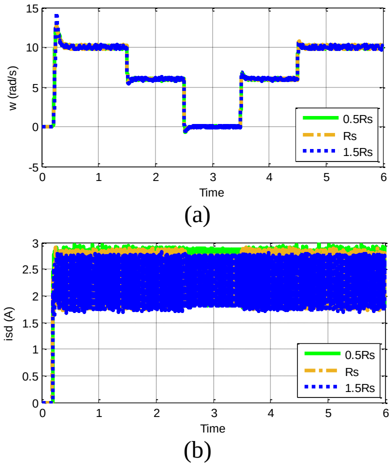
Figure 17. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for IM in no load condition (proposed method)



(a)

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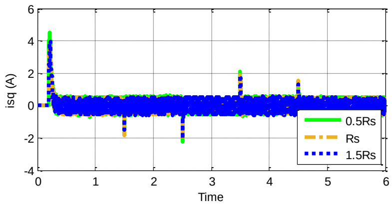
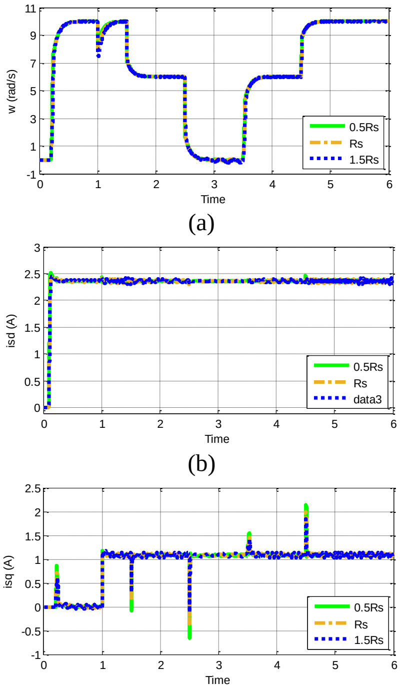


(c)

Figure 18. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for IM in no load condition (FOC method)

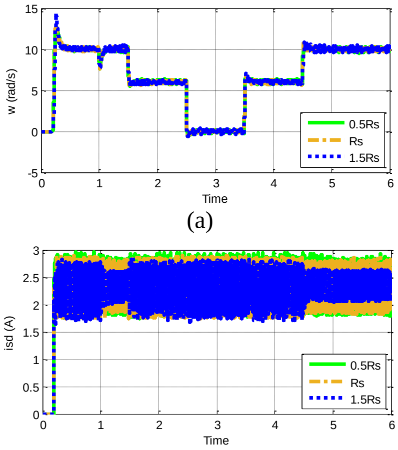


(a)

(b)

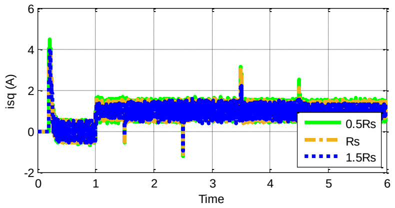
(c)

Figure 19. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for IM in 25% loaded condition (proposed method)



(a)

(b)



(c)

Figure 20. Effect of R_s variation on the (a) speed response, (b) i_{sd} response, and (c) i_{sq} response for IM in 25% loaded condition (FOC method)

6. CONCLUSION

The vector control methods are typically used for high performance application. However, the complexity and cost of driver force users to utilize simple methods in less demanding applications. Also, the most industrial users are not well prepared for modification of driver settings, which could be used for both of the IM and PMSM. In this paper, in order to overcome the mentioned difficulties, the new unified method control base on the rotor flux orientation is proposed. The proposed method is less complicated and has lower costs than FOC. The capability of the proposed controller is analyzed by theory and various simulations. The results were satisfying in both low and high speed operation. Also steady state and transient response of the proposed method was comparable to conventional methods. The effect of R_s variation on the stability has been investigated during low speed operation, with limitation of $0.5R_{s,n} \le R_s \le 1.5R_{s,n}$. For rated speeds the effect of R_s variation is not considerable.

In the proposed method, one feedback signal is omitted. Also, in order to control the q-axis current, the dynamic limiter is proposed.

Overall, the removal of the need for one PI controller, the unification method, and better current control, make it a potentially attractive control method for industrial applications.

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Novel Unified Control Method of Induction and Permanent Magnet Synchronous Motors

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چکیده

روش‌های کنترلی بسیاری برای کنترل موتورهای الکتریکی (القایی و سنکرون مغناطیس دائم) ارائه شده است که اکثرا پیچیده و غیرخطی هستند. همچنین، به ندرت در زمینه کنترل یکپارچه موتورهای الکتریکی (القایی و سنکرون مغناطیس دائم) تحقیقاتی صورت گرفته است. در این مقاله، روش کنترلی جدیدی براساس فلوی روتور محور پیشنهاد شده است. نوآوری‌های روش پیشنهادی حذف حلقه کنترلی جریان محور q (یک کنترل کننده PI) و استفاده از محدود کننده دینامیکی نرخ تغییر جریان است. هم‌چنین، برخلاف روش‌های مرسوم، روش کنترلی پیشنهادی قابلیت اعمال بر روی هر دو نوع موتور القایی و سنکرون مغناطیس دائم با کمترین تغییرات را دارد. همچنین، علاوه بر موارد مذکور، ریپل گشتاور و هارمونیک‌های جریان کاهش پیدا کرده است. مطالعات بر مبنای تئوری و نتایج شبیه‌سازی قابلیت عملکرد مناسب روش پیشنهادی در سرعت‌های کم و زیاد و برای حالت‌های ماندگار را نشان می‌دهد.

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