Standard and Modified Internal Model Control Schemes for PMSM Drive

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Abstract—**In this paper, standard internal model controller (IMC) is designed. To implement IMC method, permanent magnet synchronous motor (PMSM) drive under vector control framework is taken as an example. As IMC method is based on model of the plant, a first order model of PMSM is derived by analyzing the relationship between reference quadrature axis current and speed. For speed regulation of PMSM, standard IMC controller is designed. Second, considering the disadvantages of standard IMC method i.e. it is sensitive to the control input saturation and may give poor tracking and load disturbance performance, a modified IMC scheme is proposed, based on two-port IMC method. In modified IMC scheme, a feedback control term is added to form a composite control structure. It compensates the effect of control input saturation and improves tracking and load disturbance rejection property. Effectiveness of proposed methods has been verified by Matlab simulation results.**

Keywords—Control input saturation,disturbance rejection, PMSM, standard and modified internal model control, tracking.

I. INTRODUCTION

Most of the systems around us are non-linear systems. It is reported that due to existence of nonlinearities, uncertainties and disturbances, widely used PID controller also can not assure satisfying performance in entire operating range [1], [2]. Hence we approach towards non-linear control algorithm. Recently many non-linear algorithms have been proposed, for example, adaptive control [3]-[6], robust control [7], [8], predictive control [9], intelligent control [10], etc. These non-linear control algorithms give improved performance than traditional control algorithms.

In this paper, internal model control (IMC) method is presented. The IMC design is lucid for the following reasons: 1)controller parameters are expressed directly in certain machine parameters, 2) it separates tracking problem from regulation problem and 3) the design of controller is relatively straight forward. This method mainly based on model of the plant. So the crucial part of designing controller is modeling of the plat properly. We have different methods of modelling available like traditional mathematical modelling [11]-[13], neural networks modelling [14], fuzzy modelling [15].

For application of IMC control, permanent magnet synchronous motor (PMSM) drive is taken as example. Now a day, various types of AC motors are widely used. Among all of them PMSM is preferred because of some of its advantageous features like high efficiency, high torque to current ratio, low noise and robustness [16]. Vector control is implemented in PMSM drive to give better control performance.

Garcia and Morari firstly introduced IMC method. During some past years IMC is under research and development and hence application of IMC is extended to the motor control system from process control system[12], [13].

The IMC includes an internal model of controlled plant and an internal model controller. Whereas an internal model controller consist of an internal model of controlled plant and a low pass filter. Low pass filter is added in series with inverse of plant to make degree of denominator greater than or equal to degree of numerator. Modified design of filter is proposed in [17]. Conventional IMC method provides good tracking performance, robustness and disturbance rejection. It also provides a good platform for analysis of control system performance i.e. issues related to stability and robustness [11], [13].

It is derived that, conventional IMC method provide good disturbance rejection property for the disturbances added to the output channel but gives poor disturbance rejection performance for disturbances added to the input channel. Moreover, while designing conventional IMC, effect of control input saturation is not taken into consideration. This may degrade performance and may arise some windup problems[18]. Hence we go for modified IMC control. In [19], a two port IMC structure is proposed. In modified IMC design, a conventional feedback control loop is added to the standard IMC structure to form a composite controller. It acts as anti-windup scheme for control input saturation. It is an optimal controller design suitable as mid-way between the tracking and load disturbance rejection performances.

In this paper, firstly, a first order model of PMSM is realized by analyzing the relationship between reference quadrature axis current and speed output. Standard IMC is designed by using model of plant and a low pass filter. But as the standard IMC is sensitive to the control input saturation and provides a poor load disturbance rejection property, a modified IMC method from [19] is introduced here. It improves tracking and disturbance rejection abilities and also reduces control input saturation effect. Simulation results for both the IMC schemes are provided here to verify the effectiveness of these schemes.

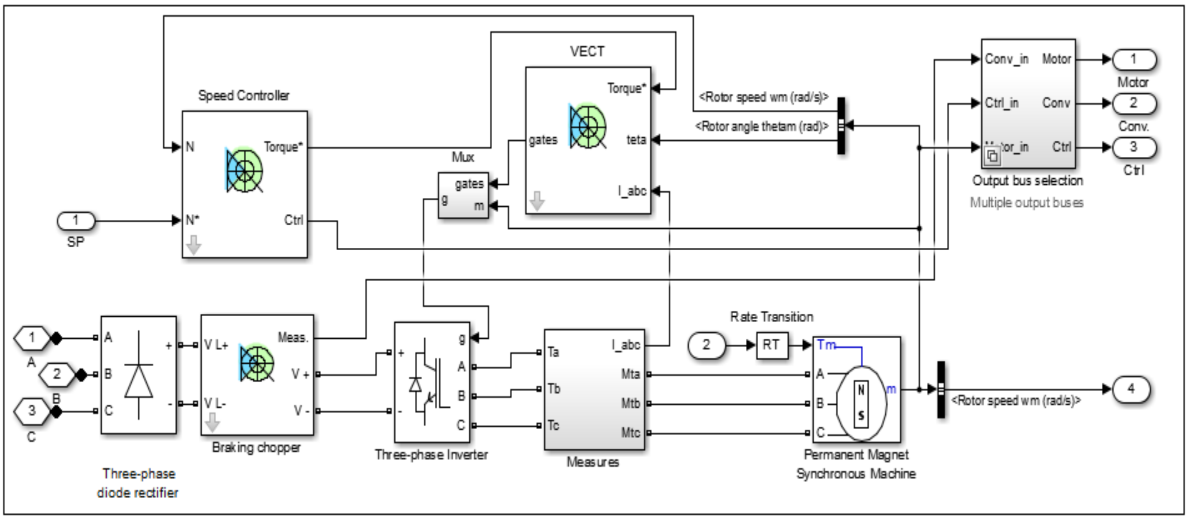


Fig.1. Principle block diagram of PMSM speed regulation system based on vector control

II. MODELLING OF PMSM

The model of surface mounted PMSM in d-q coordinates in synchronously rotating frame can be described as [20]

$$\begin{bmatrix} \dot{i}_d^* \\ \dot{i}_q^* \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & n_p\omega & 0 \\ n_p\omega & -\frac{R}{L} & \frac{n_pK_t}{J} \\ 0 & -\frac{n_pK_t}{L} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{u_d}{L} \\ \frac{u_q}{L} \\ -\frac{T_L}{J} \end{bmatrix} \quad (1)$$

where

i_d, i_q d- and q-axis stator currents, respectively;
u_d, u_q d- and q-axis stator voltages, respectively;
n_p number of pole pairs;
R stator resistance;
L stator inductance;
Ψ_f rotor flux linkage;
K_t torque constant;
ω angular velocity;
B viscous friction coefficient;
J moment of inertia;
T_L load torque

Field oriented vector control approach is a well-known strategy to control a PMSM drive [21]. Under this scheme, the torque and flux-producing components of the stator current are decoupled so that the independent torque and flux controls are possible as in dc motors. Also, a practical structure of cascade control loops, including a loop of speed and two loops of current, is employed. Usually, the *d*-axis reference current i_d^* is set to be $i_d^* = 0$ in order to approximately eliminate the couplings between angular velocity and currents. If the controllers for the two current Loops work well, the output i_d satisfies $i_d = i_d^* = 0$, and then, system (1) can be approximately reduced to the following form:

$$\begin{bmatrix} \dot{i}_q^* \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \frac{n_pK_t}{J} \\ -\frac{n_pK_t}{L} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_q \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{u_q}{L} \\ -\frac{T_L}{J} \end{bmatrix}$$

which makes the speed controller simpler.

III. CONTROL STRATEGY

1) *Standard Internal ModelController Design for PMSM*

The Standard IMC method is proved to be a robust control method which includes an internal model of controlled plant and an internal model controller which consist of an internal model of the controlled plant and a low pass filter. It can guarantee the stability of system for open loop stable plants[11], [13]. The standard IMC structure for PMSM is shown in fig 2, where the “generalized PMSM” includes the PMSM model and the other components of system, similar to that of fig. 1. $G_m(s)$ is the internal model and $C_1(s)$ is the internal model controller.

From (1), we can derive

$$\dot{\omega} = \frac{K_t i_q}{J} - \frac{B\omega}{J} - \frac{T_L}{J} = \frac{K_t i_q^*}{J} - \frac{B\omega}{J} - \frac{K_t d(t)}{J} \quad (2)$$

where $d(t) = -T_L/K_t - (i_q^* - i_q)$ represents the lumped disturbance, including the external load disturbance and the tracking error of current loop of i_q.

Therefore, the generalised PMSM (controlled model) can be described as [24]

$$G_p(\text{s})=\frac{1}{a_p s+b_p} \qquad (3)$$

where $a_p = J/K_t$, b_p=B/K_t.

The internal model is given as

$$G_m(\text{s})=\frac{1}{a_m s+b_m} \qquad (4)$$

where a_m, b_m are the internal model parameters.

For the standard IMC method, if the internal model is accurate, i.e. $G_p(\text{s}) = G_m(\text{s})$, the closed loop system is stable only if $G_p(\text{s})$ and $C_1(\text{s})$ are both stable[24]. In this case, when the internal model controller $C_1(\text{s})$ is defined as G_p^{-1}, then $\omega = \omega^*$, it means the output of the system attains input of the instantaneously. But it can be seen that, this ideal results can not be obtained due to some reasons i.e. G_p^{-1} can be hardly proper ever. Result is highly sensitive to the model errors which include non-linearity, unmodeled dynamics and so on. Hence, we design the internal model controller as follows:

$$C_1(\text{s}) = G_m^{-1}(\text{s})Q_1(\text{s}) = G_m^{-1}(\text{s})\frac{1}{\varepsilon s+1} \qquad (5)$$

where $Q_1(\text{s})$ is a low pass filter and ε is the time constant of filter.

From fig 2, it can be derived

$$\omega(s) = \frac{C(s)G_p(s)}{1+C_1(s)[G_p(s)-G_m(s)]}\omega^*(s) - \frac{G_p(s)[1-C_1(s)G_m(s)]}{1+C_1(s)[G_p(s)-G_m(s)]}\text{D(S)} \qquad (6)$$

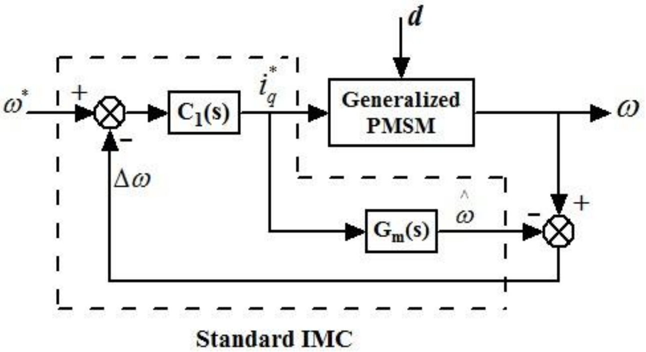


Fig. 2. Block diagram of the standard IMC method for PMSM system.

If the internal model is accurate i.e. $G_p(s) = G_m(\text{s})$, then from (5) and (6), we get

$$\omega\ (\text{s}) = \frac{1}{\varepsilon s+1}\omega^*(s) - \frac{\varepsilon s}{(a_p s+b_p)(\varepsilon s+1)}D\ (\text{s}) \qquad (7)$$

From (7), it can be derived that $G_p(s)$is included in the transfer function between ω(s) and D(s) and it affects the load disturbance rejection performance, no matterhow the parameter $\varepsilon$of the IMC filter $Q_1(\text{s})$ is tuned. Specially, for plant with large time constant, the recovery trajectory of the load disturbance rejection may have a long tail [19], [20].

In practical application, all the control systems have some type of control input saturation. Though we can make the parameter ε small enough to improve the load disturbance rejection performance (i.e. less amplitude of speed fluctuation), the output of internal model controller may exceed the saturation limit of i_q^* and hence tracking response may degrade upto some extent. Its main reason is that if there is no model error and disturbance, system will become an open loop system. Because of control input saturation, some desired information may lost, which may generate a short-sightedness property which can seriously degrade the performance of control system [23].

2) *Modified Internal Model Controller for PMSM*

To improve the abilities of tracking and load disturbance rejection of system, a feedback control term $C_2(s)$ is designed based on the standard model control framework. A modified IMC scheme is proposed using the two-port IMC structure in [22], as shown in fig 3. Note that, in real practice control input u is limited in amplitude. Thus the relationship between i_q^* and u is

$$i_q^* = \begin{cases} u, & |u| \le i_{q\ max}. \\ i_{q\ max}.sign(u), & |u| > i_{q\ max}. \end{cases}$$

The feedback control term $C_2(s)$ is designed as a proportional term simply, which is given below

$$C_2(s) = k_p \qquad (8)$$

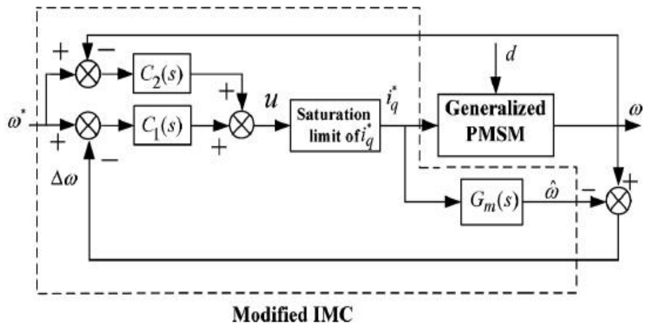


Fig. 3. Block diagram of the modified IMC method for PMSM system

For the convenience during analysis, simply consider $i_q^* = u$, regardless of saturation. From fig. 3, we can obtain

$$\omega\ (\text{s}) = \frac{[C_1(s)+C_2(s)]G_p(s)}{1+C_1(s)[G_p(s)-G_m(s)]+C_2(s)G_p(s)}\omega^*(s) - \frac{G_p(s)[1-C_1(s)G_m(s)]}{1+C_1(s)[G_p(s)-G_m(s)]+C_2(s)G_p(s)}\text{D(s)} \qquad (9)$$

If the internal model is accurate, i.e. $G_p(s) = G_m(s)$, from (5), (8) and (9), we can derive following equation

$$\omega\,(s) = \frac{(k_p\varepsilon + a_p)s + k_p + b_p}{(a_p s + k_p + b_p)(\varepsilon s + 1)}\,\omega^*(s) - \frac{\varepsilon s}{(a_p s + k_p + b_p)(\varepsilon s + 1)}\,D(s) \qquad (10)$$

To improve the load disturbance rejection performance, compared with (7), the feedback control term $k_p$canbe adjusted properly to reduce the time constant, i.e. $a_p/(b_p + k_p) < a_p/b_p$, which make the recovery trajectory in the presence of load disturbance fast to avoid "long tail". In fact, when output of modified IMC gets saturated, the output of the feedback control term C_2 can compensate the effect of control input saturation as antiwindup compensation to improve the tracking performance. The closed loop system can obtain a good ability of tracking and load disturbance rejection by adjusting the parameter k_p properly.

IV. SIMULATION TEST RESULTS

To test the performance of the standard IMC method, simulations with PMSM have been performed. PMSM drive used for these simulations is available in MATLAB drive examples.

The parameters of the PMSM used in the simulation are given as follows: number of pairs n_p = 4, stator resistance R=0.2Ω, stator inductances L= 8.5 mH, moment of inertia J_n= 0.089 kg.m^2, torque constant K_t=1.05 Nm/A and viscous coefficient B=0.005 Nms/rad.

Here, in the simulation, assuming that the internal model isaccurate, i.e. a_m=a_p=0.084761 and b_m = b_p=0.004761, we test performance of standard IMC by choosing different values of filter constant ε .

The solid lines in the fig. 4 show the response curves of speed and i_q^* under ε=0.01 where (b) is a partial enlargement graph of (a). The speed response has no overshoot and a short settling time(0.1s). As observed in section III-A1, we can reduce the value of ε to make the speed response faster theoretically. In fig. 4, the dotted lines show the response curves of speed and i_q^* under ε=0.005 without considering any saturation limit. It can be seen that, at the start-up phase of motor, the maximum value of i_q^*=1400 A for very small instance and speed response has very short settling time of 0.15s. From that start-up instance, value of i_q^* decreases very fastly. However, if we consider the control saturation, things become much different. In case of control input saturation consideration, speed response has much longer settling time.

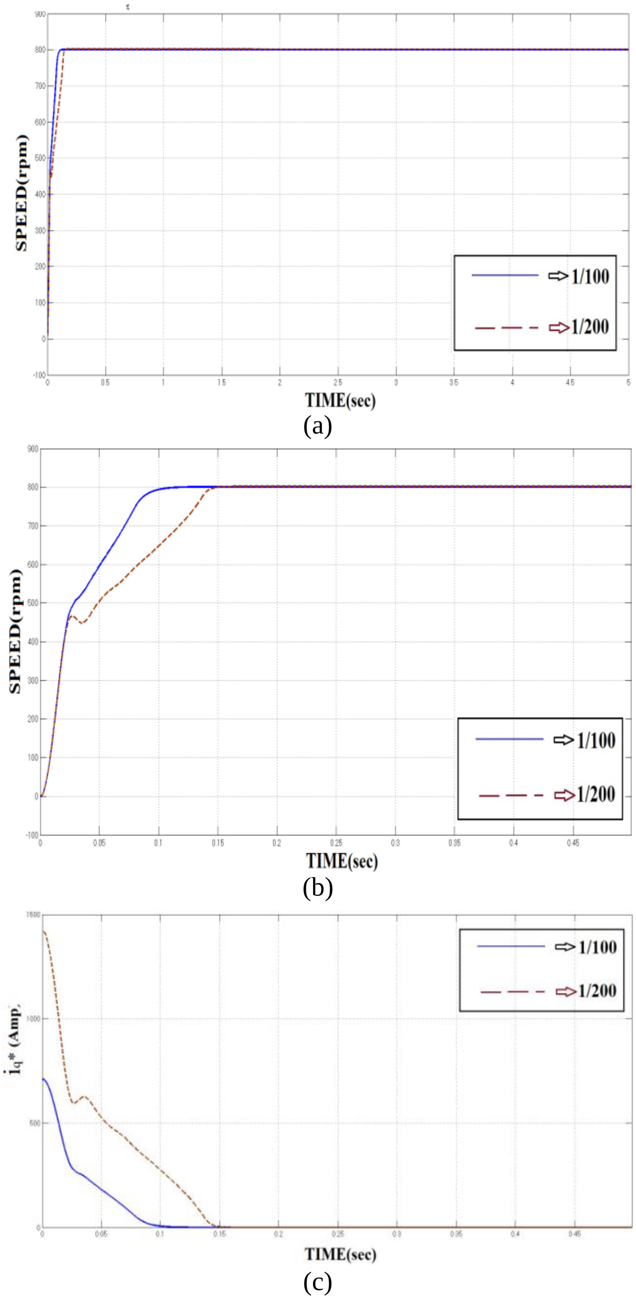
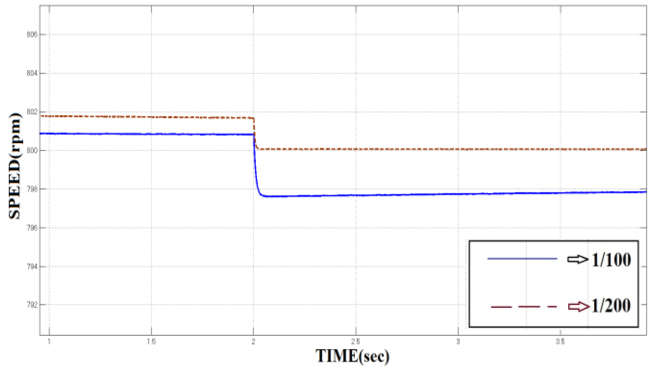
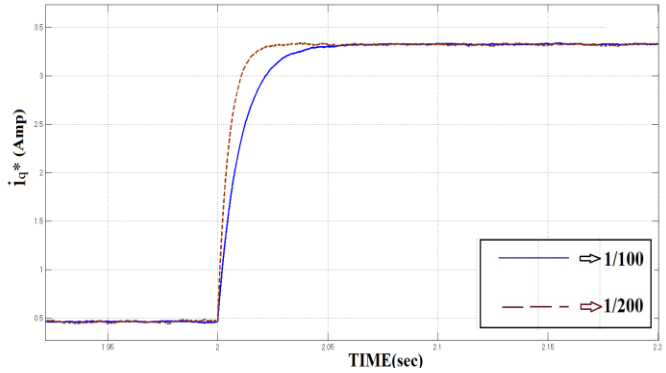


Fig. 4. Responses under standard IMC (simulation). (a) Speed. (b) Local curve of (a). (c)i_q^*.

To test the disturbance rejection performance of standard IMC method, a load torque T_L=3 N.m is applied at t=2s. As shown in fig. 5, the maximum amplitude of speed decrease under ε= 0.005 is 2 rpm. In case of ε= 0.01, decrease in amplitude is 4 and recovery time is almost same.



(a)

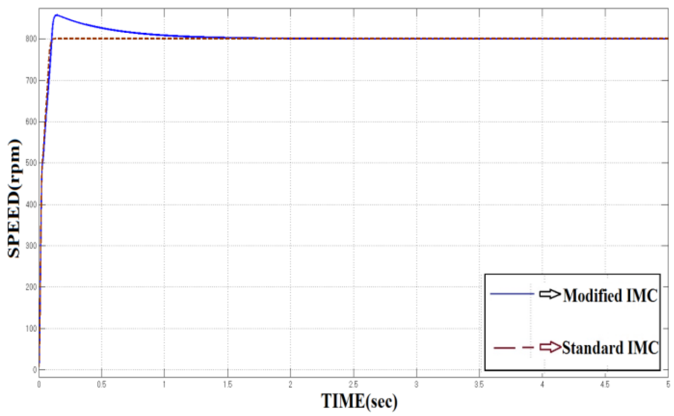


(b)

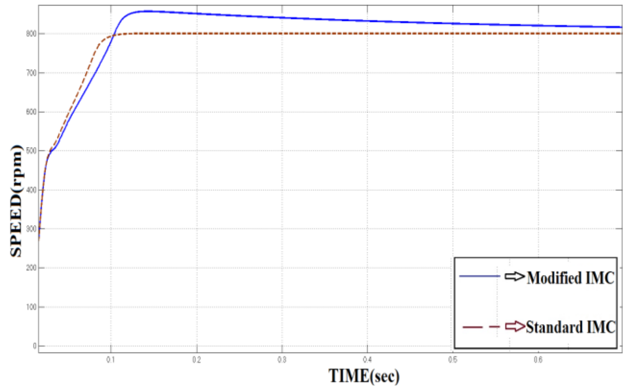
Fig. 5. Responses under standard IMC method in the presence of torque load disturbance (simulation). (a) Speed. (b) i_q^*

Here, in the simulation, the controller parameters of speed loop for modified IMC are same as standard IMC i.e. a_m=0.084761, b_m=0.004761, ε= 0.01, other motor parameters are also same as standard IMC, where, k_p=0.1875.

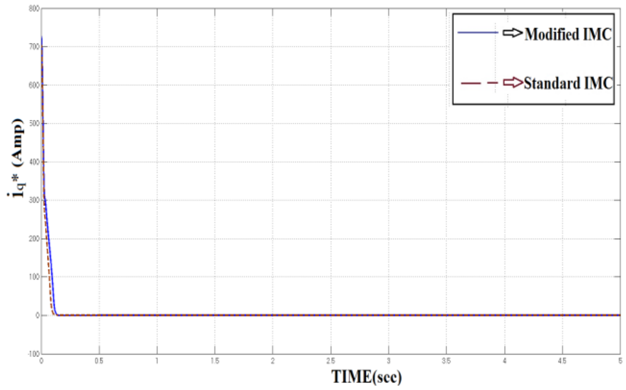
The dashed lines in the fig. 6 show the response curves of speed and i_q^* under the modified IMC. Fig. 6(b) is the partial enlargement graph of fig. 6(a). The speed response has a small overshoot and a short settling time (1.5 s). Solid lines in fig. show the results of modified IMC and dotted lines show the results of standard IMC with no overshoot.



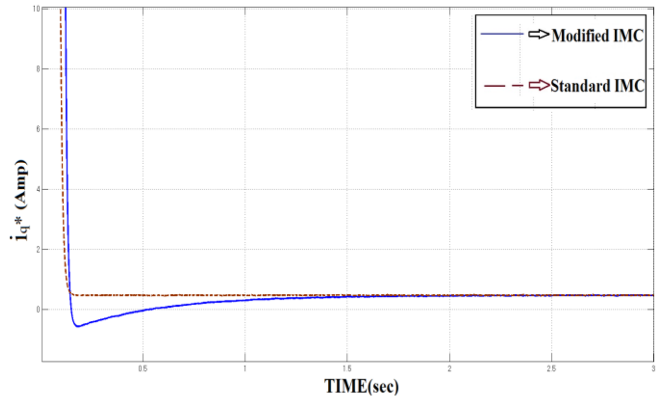
(a)



(b)



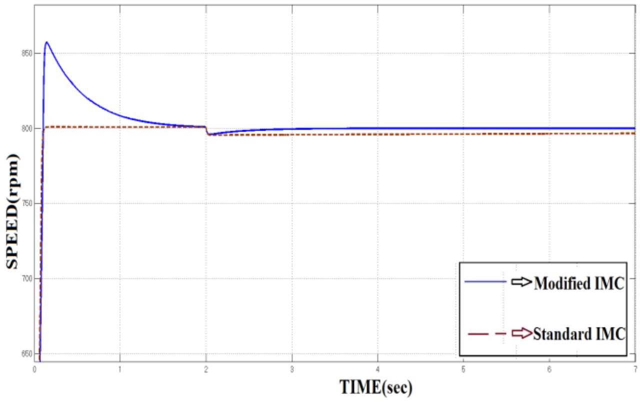
(c)



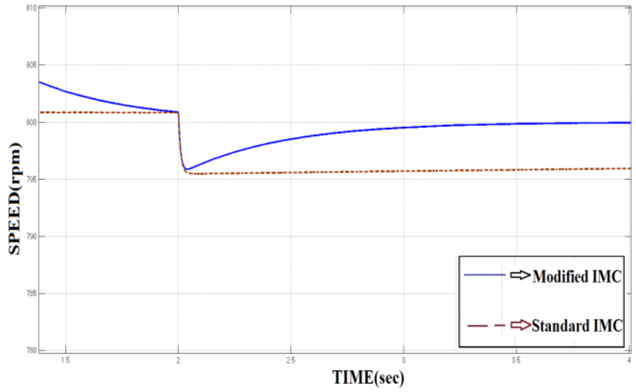
(d)

Fig. 6. Responses under standard IMC and modified IMC methods (simulation) (a) speed. (b) Local curve of (a). (c) i_q^*.(d) Local curve of (c).

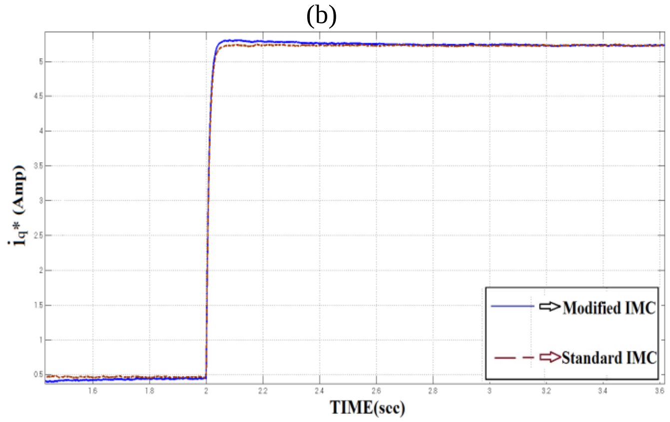
To compare disturbance rejection performance of both, standard and modified methods, a load torque T_L= 5 N.m is applied at t=2 s. As shown in fig. 7, the maximum amplitude of speed decrease under the standard IMC method is about 4 rpm and that of modified method near about 0. In case of modified IMC method, we can say that, it reduces steady state error.



(a)



(b)



(c)

Fig. 7. Responses under standard and modified IMC methods in the presence of load torque disturbance (simulation). (a) Speed. (b) Local curve of (a). (c)i_q^*

V.CONCLUSION

Standard and modified schemes of internal model control (IMC) are designed for the speed regulation problem of permanent magnet synchronous motor (PMSM)under vector control framework. A standard internal model controller, based on first order model of PMSM by analyzing the relationship between reference quadrature axis current and speed, is designed. To overcome the disadvantages of standard IMC method i.e. it is sensitive to the control input saturation and may give poor tracking and load disturbance performance, a modified IMC scheme is proposed, based on two-port IMC method. The effectiveness of the proposed methods has been verified by simulation results.

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