STANDARD AND MODIFIED INTERNAL MODEL CONTROL SCHEMES AND IMC BASED PID CONTROLLER FOR PMSM DRIVE

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Abstract - In this paper, standard internal model controller(IMC) design is presented. IMC method is implemented by taking Permanent magnet synchronous motor (PMSM) drive under vector control framework as an example. As IMC controller design mainly depends on model of the plant, a first order model of PMSM is designed by studying the relationship between speed and reference quadrature axis current. Standard IMC controller is designed for speed regulation of PMSM. Second, to overcome the disadvantages of standard IMC method i.e. it may give poor tracking and load disturbance performance and is sensitive to the control input saturation, a modified IMC scheme is presented, based on two-port IMC method. In modified IMC scheme, a composite control structure is formed by adding a feedback control term. It improves tracking and load disturbance rejection property by compensating the effect of control input saturation. Third, to compensate effect of time delay, present in real time system, IMC based PID controller is designed. IMC method is used as tuning method for conventional PID. Effectiveness of proposed methods has been proved by Matlab simulation results.

Keywords - control input saturation, dead time compensation, disturbance rejection, PMSM, standard and modified internal model control, tracking.

I. INTRODUCTION

Advanced technologies are required to control real-time systems used in industries and in daily routine as they are non-linear systems [1], [2]. Now a day, several technologies are available to deal with non-linear systems, like adaptive control [3]-[6], robust control [7], [8], predictive control [9], intelligent control [10], etc. These non-linear control algorithms give better and improved performance than traditional control algorithms.

Internal model control (IMC) method is presented in this paper. IMC method provides high performance dynamic characteristic. 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 straightforward. This method mainly based on model of the plant. Therefore, the challenging part of designing controller is modeling of the plant properly. We have various methods of modeling available like traditional mathematical modeling [11]-[13], neural networks modeling [14], fuzzy modeling [15]. IMC method also gives good solutions to process having significant time delays, which actually happens in real time environment.

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. The IMC method includes an internal model of the plant and an internal model controller, whereas an internal model controller consists of an internal model of the 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 gives good tracking performance, disturbance rejection and robustness. It also provides a good platform for analysis of control system performance i.e. issues related to robustness and stability [11], [13]. It is derived that, conventional IMC method provides good disturbance rejection property for the disturbances added to the output channel but not to disturbances added to the input channel. Moreover, while designing conventional IMC, effect of control input saturation is not taken into consideration. This may arise some windup problems and may degrade performance [18]. Hence, we approach towards modified IMC control. At two-port IMC structure is proposed in [19]. In modified IMC design, a conventional feedback control loop is added to the standard IMC structure to form a composite controller structure. It acts as anti-windup scheme for control input saturation problem. It is an optimal controller design suitable as mid-way between the tracking and load disturbance rejection performances. Time delay is always undesirable in system as it reduces stability and performance of the system. It is caused due to time taken to generate the control signals, presence of sensors in the system, transportation lag, etc. As the integral and derivative constants are function the time, performance of PID controller get affected because of dead time [20].

The conventional PID controller is still widely used in industries because of its advantageous features like simplicity and easy tuning to achieve desired time domain specifications. Many tuning methods have been suggested for the PID tuning like Chen, Hornes and Reswich (CHR) and Ziegler-Nichols (ZN) method. In this paper, IMC-PID controller tuning...
strategy is introduced here. Benefit of IMC-PID is that, it possesses advantages of both, IMC as well as PID control algorithm [20].

In this paper, firstly, a first order model of PMSM is derived by using 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 for the disturbances added from input port, a modified IMC method from [19] is introduced here. It improves tracking and disturbance rejection abilities and also reduces control input saturation effect.

Third, in real time system, a significant delay is present. So to reduce effect of time delays present in the system, IMC based PID is designed, which is presented. So to reduce effect of time delays present in the system, IMC based PID is designed, which is considered as time delay compensator [20]. Simulation results for both the IMC schemes and IMC-PID method are provided here to verify the effectiveness of these schemes.

Field oriented vector control approach is a famous and successful strategy to control synchronous drive [22]. Under this scheme, the torque ($i_q$) and flux-producing components ($i_d$) of the stator current are decoupled so that the independent torque and flux controls are possible as in dc motors. 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 $i_q$ satisfies $i_q = i_d^* = 0$, and then, system (1) can be approximately reduced to the following form:

$$
\begin{bmatrix}
\dot{i}_d \\
\dot{i}_q
\end{bmatrix} =
\begin{bmatrix}
\frac{-R}{L} & \frac{n_p \omega}{L} \\
\frac{n_p K_t}{L} & \frac{-B}{L}
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
+ \begin{bmatrix}
u_d \\
u_q
\end{bmatrix} - \begin{bmatrix}
\frac{u_d}{L} \\
\frac{u_q}{L}
\end{bmatrix}
\begin{bmatrix}
\frac{1}{\omega}
\end{bmatrix}
$$

which makes the speed controller design simpler.

### III. CONTROL STRATEGY

1) Standard Internal Model Controller Design for PMSM

The Standard IMC method guarantees 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

$$\dot{\omega} = \frac{K_t i_q}{J} - \frac{B \omega}{J} - \frac{T_L}{J} = \frac{K_t i_q}{J} - \frac{B \omega}{J} - \frac{K_t i_q}{J}$$

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

Therefore, the generalised PMSM (controlled model) can be described as [25]

$$G_p(s) = \frac{1}{\alpha s + b_p}$$

where $\alpha_p = 1/K_t$, $b_p = B/K_t$.

The internal model is given as

$$G_m(s) = \frac{1}{\alpha_m s + b_m}$$

where $\alpha_m, b_m$ are the internal model parameters. For the standard IMC method, if the internal model is accurate, i.e. $G_p(s) = G_m(s)$, the closed loop system is stable only if $G_p(s)$ and $C_1(s)$ are both stable [24]. In this case, when the internal model controller $C_1(s)$ is defined as $G_p^{-1}$, the output of the system tracks input of the system, it means $\omega = \omega^*$. But it can be
seen that, this ideal results can not be obtained due to some reasons like $G_p^{-1}$ can be hardly proper ever i.e. there is always some part of system which is non-invertible. 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:

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

\(Q_1(s)\) is a low pass filter and \(\varepsilon\) is the time constant of filter.

From fig 2, it can be derived

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

From (7), it can be derived that the transfer function between \(\omega(s)\) and \(D(s)\) includes \(G_p(s)\) and it affects the load disturbance rejection performance, though the parameter of the IMC filter \(Q_1(s)\) is tuned perfectly. Specially, for plant with large time constant, the recovery time of the load disturbance rejection might be large[19], [21].

In practical application, the output of internal model controller may exceed the saturation limit of \(i_q^*\) and hence tracking response may degrade up to some extent. 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 [24]. Though we got model exact same as plant, then error will become zero and system will become open loop system. Closed loop control will be lost. Therefore, we approach towards modified IMC method.

2) Modified Internal Model Controller for PMSM

To overcome the disadvantages of standard IMC method and to improve the abilities of tracking and load disturbance rejection of system, a feedback control term \(C_2(s)\) is added to the standard model control framework. A modified IMC scheme is proposed using the two-port IMC structure in [23], 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

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

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

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

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

$$\omega(s) = \frac{[c_1(s)+c_2(s)]G_p(s)}{1+c_1(s)[G_p(s)-G_m(s)]+c_2(s)G_p(s)} \omega^*(s) - \frac{1}{1+c_1(s)[G_p(s)-G_m(s)]+c_2(s)G_p(s)}D(s) \quad (9)$$

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

$$\omega(s) = \frac{k_p(s+c_p)u + b_p}{s(a_p s + b_p)(s+1)} \omega^*(s) - \frac{1}{s(a_p s + b_p)(s+1)}D(s) \quad (10)$$

To improve the load disturbance rejection performance, compared with (7), the feedback control term \(k_p\) can be adjusted properly to reduce the time constant, i.e. to make \(a_p/(b_p + k_p) < a_p/b_p\), it reduces recovery time in the presence of load disturbance. 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.

3) IMC based PID

The IMC structure is rearranged to get a standard feedback control system so that open loop unstable system can be handled. This arrangement improves input disturbance rejection performance. As in IMC design, IMC based PID structure uses the process model. The IMC results in only one tuning parameter, which is filter-tuning factor, but in the IMC based PID; tuning parameters are functions of this tuning factor [26]. The selection of the filter parameter is directly related to the robustness. IMC based PID procedure uses an approximation for the dead time. Moreover, it gives the same performance as IMC does if process has no delays [27].

IMC structure can be rearranged as follows

$$C(s) = \frac{\frac{a_m}{\tau_f s + 1}}{1 - \frac{a_m}{\tau_f s + 1}}$$

so we get a standard feedback structure as follows

Transfer function of controller $C(s)$ can be given as follows

$$C(s) = \frac{a_m}{\tau_f s + 1}$$

Comparing transfer function of controller $C(s)$ with transfer function of ideal PI controller as follows

$$C(s) = \frac{a_m}{\tau_f s + 1}$$

We get,

$$K_c = \frac{a_m}{\tau_f}$$

Following table gives the idea of model format and its respective integral constant ($\tau_f$), derivative constant ($\tau_d$), and system constant ($K_c$).

<table>
<thead>
<tr>
<th>IMC</th>
<th>Process</th>
<th>Input</th>
<th>$\tau_f$</th>
<th>$\tau_d$</th>
<th>$K_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{a_m}{\tau_f s + 1}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{a_m}{\tau_f s + 1}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{a_m}{\tau_f s + 1}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{a_m}{\tau_f s + 1}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
</tr>
<tr>
<td>5</td>
<td>$\frac{a_m}{\tau_f s + 1}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
<td>$\frac{1}{s}$</td>
</tr>
</tbody>
</table>

$\lambda$ is the only tuneable parameter

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 $R = 0.2 \Omega$, stator inductances $L = 8.5 \text{ mH}$, moment of inertia $J_f = 0.039 \text{ kg.m}^2$, torque constant $K_t = 1.05 \text{ Nm/A}$ and viscous coefficient $B = 0.005 \text{ Nms/rad}$.

Here, in the simulation, assuming that the internal model is inaccurate, i.e. $a_m = a_p = 0.0371428$ and $b_m = b_p = 0.004761$, we test performance of standard IMC by choosing different values of filter constant.

The solid lines in the fig. 4 show the response curves of speed and $i_q^*$ under $\epsilon = 0.01$ where (b) is a partial enlargement graph of (a). The speed response has no overshoot and a short settling time (0.12s). As observed in section III-A1, we can reduce the value of $\epsilon$ to make the speed response faster theoretically.

In fig. 4, the dotted lines show the response curves of speed and $i_q^*$ under $\epsilon = 0.005$ without considering any saturation limit. It can be seen that, at the start-up phase of motor, the maximum value of $i_q^*$ is 1100A 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.
To compare disturbance rejection performance of both, standard and modified methods, a load torque $T_L = 4 \text{ N,m}$ is applied at $t=2 \text{ s}$. As shown in fig. 8, 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 delay of 0.2 sec is inserted in system so as to prove the effectiveness of IMC-PID controller. All the other system parameters are same as used for standard and modified IMC and model parameters are also same i.e. \( a_m = a_p = 0.0371428 \) and \( b_m = b_p = 0.004761 \). Value of filter constant \( \varepsilon \) is varied. System response is shown for \( \varepsilon = 0.005, 0.01 \) and 0.05. From the graph it can be seen that, as value of \( \varepsilon \) decreases, settling time of system decreases but sensitivity increases and vice versa. So for the robust and fast response, we have to choose optimum value of \( \varepsilon \).

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 studying 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. To compensate the effect of time delay, present in real systems, IMC based PID is designed. It proves very effective and robust at industrial level.

The effectiveness of the proposed methods has been verified by simulation results and comparison is also shown between all the proposed methods.

REFERENCES


