Quantitative design and implementation of PI-D controller with model-following response for motor drive

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Abstract: The authors present the quantitative design and implementation of a PI-D 2-degrees-of-freedom controller (2DOFC) for motor drives. The proposed 2DOF controller consists of a PI-D feedback (also called the PI plus rate feedback) controller and a command feedforward controller. A quantitative design procedure is derived to find the parameters of a 2DOF controller systematically according to the given motor drive specifications. In addition to the tracking and regulation speed control specifications, the effects of command change rate as well as control effort are also considered in the proposed design procedure. As the operation condition changes occur, a model-following controller (MFC) is added to preserve the control specifications. The analysis and design of the proposed controller for the speed control of an induction motor drive are described in detail, and some simulation and measured results are provided to show its performance.

1 Introduction

Motor drives are the most important actuators for much industrial equipment. Generally, motor drives must have the following step command tracking and load regulation speed responses, simultaneously: (i) fast command tracking response without overshoot, oscillation and steady-state error; (ii) the dynamic speed response due to step load change must have small dip and short restore time, no oscillation around set-point and zero steady-state error; (iii) the control performance is independent of system operating condition changes; and (iv) since severe control saturation may lead to a large overshoot and stability problem, the limitation of control effort should also be considered.

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Till now, many control techniques [1–6] have been developed for motor drives to yield good performance. These methods have the common drawbacks: (i) the aforementioned control requirements cannot be satisfied simultaneously; (ii) lack of a quantitative design procedure to find the controller parameters. The proportional-plus-integral (PI) controller is very commonly used owing to its simplicity. A PI-based 2DOFC for motor drive speed control has been developed in [7], where a quantitative design method was derived for finding the controller parameters to meet the prescribed tracking and regulation control specifications. However, the effect of control effort limitation was not considered.

The proportional-plus-integral-plus-derivative (PID) controller is also one of the most commonly used controllers in industrial applications owing to its tuning flexibility and ease of design and implementation [8–13]. Depending on the particular applications, there are still other modified structures of the standard PID controller, such as PI-D and I-PD controllers [8, 9]. A PID controller possesses three parameters, which can be tuned to meet the desired tracking transient and static responses. Although some tuning techniques [10–13] have been proposed for systematically finding the parameters of a PID controller, it still lacks of a quantitative design method. In addition, the requirements of a high-performance motor drive mentioned above still cannot be satisfied completely by the existing methods.

In this paper, a PI-D-based 2DOFC having good model-following response for a motor drive and its design procedure are presented. In the proposed controller, a PI-D feedback controller is augmented with a command feedforward controller to form a 2-degrees-of-freedom structure. Based on the nominal plant model and the prescribed control specifications of the motor drive described above, a design procedure is developed to find the controller parameters systematically and quantitatively. In the design process, the effects of command change rate as well as control effort limitation are also considered. To reduce the response trajectory deviation due to operating condition changes, a reference model having the desired tracking response for the nominal case is found, and a model-following error-driven control signal is generated to improve the tracking response. In addition, the regulation response can also be further improved by adding the model-following controller.

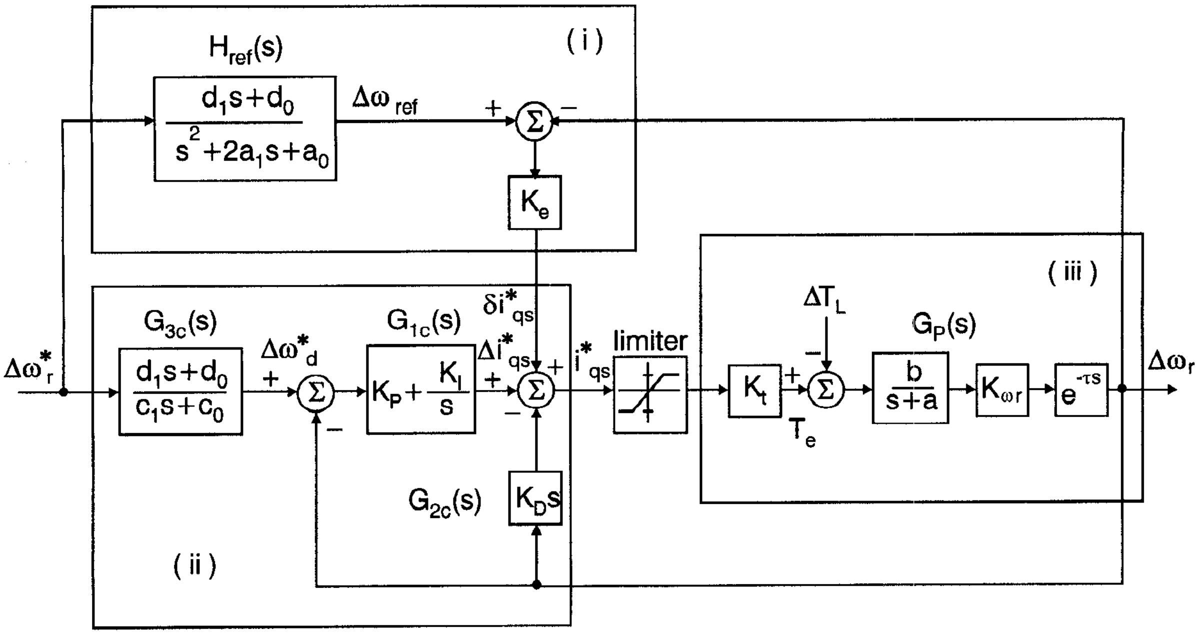

Fig. 1 *Configuration of proposed speed controller for motor drive*
(i) Model-following controller; (ii) PI-D 2DOF controller; (iii) drive system

The induction motor is the most commonly used motor owing to its structural advantages [1]. Thus, the application of the proposed PI-D 2DOFC to its speed control is made. First, the dynamic model of an indirect field-oriented induction motor drive for the nominal case is estimated. Then the design and implementation of the proposed speed controller are performed. Some simulated and measured results are provided to verify the effectiveness of the proposed controller.

2 Statement of problem

To achieve the control requirements of a high-performance motor drive described in Section 1, the configuration of the proposed controller is shown in Fig. 1. The transfer function and the corresponding dynamic equation of a typical motor drive are [1, 5–7]:

$$G_p(s) = \frac{1/J}{s+B/J} \triangleq \frac{b}{s+a}$$
$$\underline{J} < J < \overline{J}, \quad \underline{B} < B < \overline{B}$$
$$\underline{a} < a < \overline{a}, \quad \underline{b} < b < \overline{b} \qquad (1)$$

$$T_e(t) = K_t i_{qs}^*(t)$$
$$= J\frac{d}{dt}K_{\omega r}\Delta\omega_r(t-\tau) + BK_{\omega r}\Delta\omega_r(t-\tau) + \Delta T_L(t) \qquad (2)$$

where K_t is the torque generating constant, $K_{\omega r}$ is the conversion constant of the speed sensor, τ is the dead time, and $J(= J_{motor} + J_{load})$ and $B(= B_{motor} + B_{load})$ are the total mechanical inertia constant and damping coefficient, respectively, which are varied – particularly the value of J_{load}. The design philosophy of the proposed control system is arranged as follows.

PI-D 2DOF controller:

(i) The drive model for the nominal case is estimated [14].

(ii) The specifications of the motor drive are given as:

(*a*) *speed response due to step command change*

response time (the time at which the tracking response rose from zero to 90% of the final value) $= t_{re}$

overshoot = 0

steady-state error = 0

maximum value of control force $(i_{qs}^*) = i_{qsm}^*$

(*b*) *speed response due to step load change*

steady-state error = 0

maximum speed dip $(\Delta T_L = 1\ \text{Nm}) = \Delta\omega_{dm}$

Figs. 2*a* and *b* show the desired drive speed responses, where I_{limit} is the limit value of the controller output.

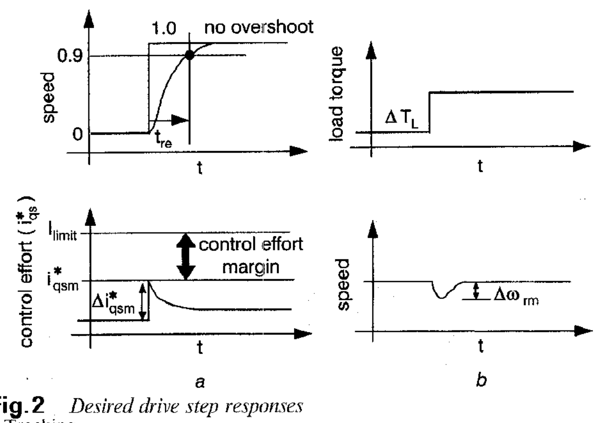

Fig. 2 *Desired drive step responses*
a Tracking
b Regulation

(iii) The PI-D 2DOFC consists of a PI-D feedback controller (G_{1c}, G_{2c}) and a command feedforward controller (G_{3c}), which are designed using the procedure derived later according to the drive dynamic model for the nominal case and the given specifications.

Ramp speed command: As the magnitude of the step command change increased, the control effort is also increased. To avoid the control saturation, the ramp command with a suitable change rate is derived and applied alternatively.

Model-following controller:

(i) The closed-loop transfer function $H_{dr}(s) \triangleq \Delta\omega_r(s)/\Delta\omega_r^*(s)$ of the drive system controlled by the designed PI-D 2DOFC for the nominal case is found. It represents the desired tracking response trajectory, so it is chosen as the reference model.

(ii) As the operating condition change occurred, a model-following control signal $\delta i_{qs}^* = K_e(\Delta\omega_{ref} - \Delta\omega_r)$ is generated to let the drive speed tracking response closely follow that generated by the reference model, and the load regulation response can also be further improved.

3 Quantitative design procedure of proposed PI-D 2DOF controller

3.1 Preliminary derivations

The structures of the controllers G_{1c}, G_{2c} and G_{3c} shown in Fig. 1 are set to be:

$$G_{1c}(s) = K_p + \frac{K_I}{s}, \quad G_{2c}(s) = K_D s \tag{3}$$

$$G_{3c}(s) = \frac{d_1 s + d_0}{c_1 s + c_0} \tag{4}$$

The PI-D feedback controller (G_{1c} and G_{2c}) and the command feedforward controller (G_{3c}) provide 2 degrees of freedom to handle the tracking and regulation control problems simultaneously. The derivative controller is placed on the feedback path for avoiding the overrun problem due to the step command change. Before introducing the design of the proposed controller, some transfer functions and system performance variables are derived from Fig. 1. The dead time is first neglected in the following derivations, and its effect on the control performance will be observed thereafter.

Load regulation characteristics: The speed change to the load torque change transfer function can be found as

$$\begin{aligned} H_{dd}(s) &\triangleq \left.\frac{\Delta\omega_r(s)}{\Delta T_L(s)}\right|_{\Delta\omega_d^*=0} \\ &= \frac{-K_{\omega r}G_P(s)}{1 + K_t K_{\omega r} G_P(s)[G_{1c}(s) + G_{2c}(s)]} \\ &\triangleq \frac{-b_0 s}{s^2 + 2a_1 s + a_0} \\ &\triangleq \frac{-b_0 s}{(s+\mu_1)(s+\mu_2)} \end{aligned} \tag{5}$$

where:

$$\begin{aligned} a_1 &= \frac{a + K_t K_P b K_{\omega r}}{2(1 + K_t K_D b K_{\omega r})} \\ a_0 &= \frac{K_t K_I b K_{\omega r}}{1 + K_t K_D b K_{\omega r}} \\ b_0 &= \frac{b K_{\omega r}}{1 + K_t K_D b K_{\omega r}} \end{aligned} \tag{6}$$

$$\mu_1 + \mu_2 = 2a_1, \quad \mu_1\mu_2 = a_0 \tag{7}$$

The speed regulation response due to the step load change ΔT_L can be found from eqn. 5 to be

$$\Delta\omega_r(t) = -\frac{\Delta T_L b_0}{\mu_2 - \mu_1}[\exp(-\mu_1 t) - \exp(-\mu_2 t)] \tag{8}$$

From eqn. 8 one can derive the maximum speed dip,

$$\begin{aligned} \Delta\omega_{dm} = -\frac{\Delta T_L b_0}{\mu_2 - \mu_1}\Bigg[&\exp\left(-\frac{\mu_1}{\mu_2-\mu_1}\ln\frac{\mu_2}{\mu_1}\right) \\ &- \exp\left(-\frac{\mu_2}{\mu_2-\mu_1}\ln\frac{\mu_2}{\mu_1}\right)\Bigg] \end{aligned} \tag{9}$$

Command tracking characteristics:

(i) tracking speed transfer function without $G_{3c}(s)$,

$$\begin{aligned} H_{dr}^*(s) &\triangleq \left.\frac{\Delta\omega_r(s)}{\Delta\omega_d^*(s)}\right|_{\Delta T_L=0} \\ &= \frac{K_t K_{\omega r} G_{1c}(s) G_P(s)}{1 + K_t K_{\omega r} G_P(s)[G_{1c}(s) + G_{2c}(s)]} \\ &\triangleq \frac{b_1 s + a_0}{s^2 + 2a_1 s + a_0} \end{aligned} \tag{10}$$

where a_0 and a_1 are listed in eqn. 6, and

$$b_1 = \frac{K_t K_P b K_{\omega r}}{1 + K_t K_D b K_{\omega r}} \tag{11}$$

(ii) tracking speed transfer function with $G_{3c}(s)$. By letting $c_1 = b_1$ and $c_0 = a_0$ in eqns. 4 and 10, one can find

$$\begin{aligned} H_{dr}(s) &\triangleq \left.\frac{\Delta\omega_r(s)}{\Delta\omega_r^*(s)}\right|_{\Delta T_L=0} \\ &= \frac{d_1 s + d_0}{s^2 + 2a_1 s + a_0} \\ &\triangleq \frac{d_1 s + d_0}{(s+\mu_1)(s+\mu_2)} \\ &= \frac{h_1}{(s+\mu_1)} + \frac{h_2}{(s+\mu_2)} \end{aligned} \tag{12}$$

with

$$d_0 = h_1\mu_2 + h_2\mu_1 \quad d_1 = h_1 + h_2 \tag{13}$$

The speed response due to the step command change $\Delta\omega_r^*$ found from eqn. 12 is

$$\Delta\omega_r(t) = \Delta\omega_r^*\left[\frac{h_1}{\mu_1}(1 - e^{-\mu_1 t}) + \frac{h_2}{\mu_2}(1 - e^{-\mu_2 t})\right] \tag{14}$$

(iii) condition of zero overshoot. Many conditions for zero overshoot of the step tracking response can be derived. The one derived in [7] is applied here. For the second-order system of eqn. 12, the zero overshoot condition is as follows:

$$h_1 = \left(\frac{\mu_1}{\mu_2}\right)^{\frac{1}{2}} h_2, \quad \mu_2 > \mu_1 \tag{15}$$

(iv) Maximum torque current (control force) Δi_{qsm}^*. The transfer function between Δi_{qs}^* to command $\Delta\omega_r^*$ can be derived from Fig. 1 as

$$\begin{aligned} H_{di}(s) &\triangleq \left.\frac{\Delta i_{qs}^*(s)}{\Delta\omega_r^*(s)}\right|_{\Delta T_L=0} \\ &= \frac{G_{3c}(s) G_{1c}(s)}{1 + K_t K_{\omega r} G_P(s)[G_{1c}(s) + G_{2c}(s)]} \\ &= \frac{d_1 s^2 + (a d_1 + d_0)s + d_0}{K_t b K_{\omega r}(s^2 + 2a_1 s + a_0)} \\ &= \frac{d_1 s^2 + (a d_1 + d_0)s + d_0}{K_t b K_{\omega r}(s+\mu_1)(s+\mu_2)} \end{aligned} \tag{16}$$

The current response due to the step command change of $\Delta\omega_r^*$ is found from eqn. 16 as

$$\begin{aligned} \Delta i_{qs}^*(t) = \frac{\Delta\omega_r^*}{K_t b K_{\omega r}}\Bigg\{&\frac{h_1}{\mu_1}[a + (\mu_1 - a)e^{-\mu_1 t}] \\ &+ \frac{h_2}{\mu_2}[a + (\mu_2 - a)e^{-\mu_2 t}]\Bigg\} \end{aligned} \tag{17}$$

The first and second derivatives of Δi_{qs}^* are:

$$\frac{d}{dt}\Delta i_{qs}^*(t) = \frac{\Delta\omega_r^*}{K_t b K_{\omega r}}[-h_1(\mu_1 - a)e^{-\mu_1 t} - h_2(\mu_2 - a)e^{-\mu_2 t}] \quad (18)$$

$$\frac{d^2}{dt^2}\Delta i_{qs}^*(t) = \frac{\Delta\omega_r^*}{K_t b K_{\omega r}}[\mu_1 h_1(\mu_1 - a)e^{-\mu_1 t} + \mu_2 h_2(\mu_2 - a)e^{-\mu_2 t}] \quad (19)$$

From eqn. 15, one can observe that $d\Delta i_{qs}^*(t)/dt < 0$, $t \geq 0$, so $\Delta i_{qs}^*(t)$ is a decreasing time function, and its maximum value occurring at $t = 0$ is

$$\Delta i_{qsm}^* = \Delta i_{qs}^*(0) = \frac{\Delta\omega_r^*}{K_t b K_{\omega r}}(h_1 + h_2) = \frac{\Delta\omega_r^* d_1}{K_t b K_{\omega r}} \quad (20)$$

The actual maximum torque current is equal to $i_{qsm}^* = \Delta i_{qsm}^* + i_{qs}^*(0)$, with $i_{qs}^*(0)$ being the torque current at the operating point.

3.2 Design of PI-D 2DOF controller

A set of nonlinear equations corresponding to the desired motor drive control specifications can be derived and listed in eqns. 21–25. For the step speed tracking response, the zero steady-state error, the zero overshoot, the prescribed response time and the desired maximum torque current are represented in eqns. 21–24 using eqns. 12, 15, 14 and 20, respectively. As to the step load regulation response, eqn. 25, describing the desired maximum speed dip, is derived from eqn. 9:

$$f_1(h_1, h_2, \mu_1, \mu_2, b_0) = \frac{h_1}{\mu_1} + \frac{h_2}{\mu_2} - 1 = 0 \quad (21)$$

$$f_2(h_1, h_2, \mu_1, \mu_2, b_0) = h_1 - \left(\frac{\mu_1}{\mu_2}\right)^{\frac{1}{2}} h_2 = 0 \quad (22)$$

$$f_3(h_1, h_2, \mu_1, \mu_2, b_0) = 0.9 - \left[\frac{h_1}{\mu_1}(1 - e^{-\mu_1 t_{re}}) + \frac{h_2}{\mu_2}(1 - e^{-\mu_2 t_{re}})\right] = 0 \quad (23)$$

$$f_4(h_1, h_2, \mu_1, \mu_2, b_0) = \Delta i_{qsm}^* - \frac{\Delta\omega_r^*}{K_t b K_{\omega r}}(h_1 + h_2) = 0 \quad (24)$$

$$f_5(h_1, h_2, \mu_1, \mu_2, b_0) = \Delta\omega_{dm} + \frac{\Delta T_L b_0}{\mu_2 - \mu_1}\left[\exp\left(-\frac{\mu_1}{\mu_2 - \mu_1}\ln\frac{\mu_2}{\mu_1}\right) - \exp\left(-\frac{\mu_2}{\mu_2 - \mu_1}\ln\frac{\mu_2}{\mu_1}\right)\right] = 0 \quad (25)$$

The parameters of h_1, h_2, μ_1, μ_2, b_0 can be solved from eqns. 21–25 using the PCMATLAB package, and then they are substituted into eqns. 6, 7 and 13 to yield the parameters of controllers $G_{1c}(s)$, $G_{2c}(s)$ and $G_{3c}(s)$ as:

$$K_P = \frac{1}{K_t b}\left(\frac{2a_1 b_1}{b_0} - \frac{a}{K_{\omega r}}\right)$$
$$K_I = \frac{a_0}{K_t b_0}$$
$$K_D = \frac{1}{K_t b K_{\omega r}}\left(\frac{b}{b_0}K_{\omega r} - 1\right) \quad (26)$$

$$d_0 = h_1\mu_2 + h_2\mu_1 \quad d_1 = h_1 + h_2 \quad c_0 = a_0 \quad c_1 = b_1 \quad (27)$$

Comments about specifying specifications: In the design process of the proposed controller, one can find that the smaller the values of t_{re} or $\Delta\omega_{dm}$ specified, the larger are the values of controller parameters yielded. Since the torque current requirement due to command change is larger than that due to load torque change, only the former is considered. Many values of i_{qsm}^* can be specified for the same other drive specifications, but too large a value of i_{qsm}^* may lead to undesirably large values of the controller parameters. Also, the larger gains, which result from the larger values of i_{qsm}^* specified, will amplify the noise to affect the operating performance of the drive, so they should be avoided. According to these observations, the general rules for specifying i_{qsm}^* are given as follows: (i) i_{qsm}^* [$= \Delta i_{qsm}^* + i_{qs}^*(0)$] $< I_{limit}$, where I_{limit} is the limit value of the limiter at the controller output; and (ii) i_{qsm}^* is chosen as small as possible for a reasonable solution to be solved.

4 Ramp command for large value of setpoint change

The step command change with large magnitude may not be appropriate in a real application, since it will lead to hard control saturation and a large overshoot in response. To solve this problem, the ramp command with proper change rate is proposed. The ramp command is

$$\omega_r^*(t) = \begin{cases} K_r t, & K_r = h_r/\tau_r \quad 0 \leq t \leq \tau_r \\ h_r & \tau_r \leq t \end{cases} \quad (28)$$

where τ_r denotes the rise time and h_r is the final value of the command. The Laplace transform of $\omega_r^*(t)$ is

$$\omega_r^*(s) = \frac{K_r}{s^2} - \frac{K_r}{s^2}e^{-\tau_r s} \quad (29)$$

From eqns. 12, 16 and 29, the rotor speed and torque current responses for this type of command can be derived as:

$$\omega_r(t) = K_r\left\{\left[\frac{h_2}{\mu_2^2}(e^{-\mu_2 t} - 1) + \frac{h_1}{\mu_1^2}(e^{-\mu_1 t} - 1) + \left(\frac{h_1}{\mu_1} + \frac{h_2}{\mu_2}\right)t\right] - \left[\frac{h_2}{\mu_2^2}(e^{-\mu_2(t-\tau_r)} - 1) + \frac{h_1}{\mu_1^2}(e^{-\mu_1(t-\tau_r)} - 1) + \left(\frac{h_1}{\mu_1} + \frac{h_2}{\mu_2}\right)(t - \tau_r)\right]u(t - \tau_r)\right\} \quad (30)$$

$$\Delta i_{qs}^*(t) = \frac{K_r}{K_t b K_{\omega r}}\left\{\left[-\frac{(\mu_2 - a)h_2}{\mu_2^2}e^{-\mu_2 t} - \frac{(\mu_1 - a)h_1}{\mu_1^2}e^{-\mu_1 t} + a\left(\frac{h_1}{\mu_1} + \frac{h_2}{\mu_2}\right)t + B_1\right] + \left[\frac{(\mu_2 - a)h_2}{\mu_2^2}(e^{-\mu_2(t-\tau_r)} - 1) + \frac{(\mu_1 - a)h_1}{\mu_1^2}(e^{-\mu_1(t-\tau_r)} - 1) - a\left(\frac{h_1}{\mu_1} + \frac{h_2}{\mu_2}\right)(t-\tau_r) + B_1\right]u(t-\tau_r)\right\} \quad (31)$$

where

$$B_1 = \frac{1}{a_0^2}[aa_0(h_1 + h_2) + a_0(h_1\mu_2 + h_2\mu_1) - 2aa_1(h_1\mu_2 + h_2\mu_1)]$$

From eqn. 31 we find that

$$\frac{d}{dt}\Delta i_{qs}^*(t) > 0, \quad \forall t < \tau_r$$

and

$$\frac{d}{dt}\Delta i_{qs}^*(t) < 0, \quad \forall t > \tau_r \tag{32}$$

The maximum torque current in this case can be found from eqns. 31 and 32 as

$$\begin{aligned}\Delta i_{qsm}^* &= \Delta i_{qs}^*(\tau_r) \\ &= \frac{K_r}{K_t b K_{\omega r}}\left[-\frac{(\mu_1 - a)h_1}{\mu_1^2}e^{-\mu_1\tau_r} - \frac{(\mu_2 - a)h_2}{\mu_2^2}e^{-\mu_2\tau_r} + a\left(\frac{h_1}{\mu_1} + \frac{h_2}{\mu_2}\right)\tau_r + B_1\right]\end{aligned} \tag{33}$$

Given Δi_{qsm}^* and the magnitude h_r of the ramp command, the rise time τ_r can be solved from eqn. 33. By expressing the rise time as a function of h_r using a curve fitting technique, i.e. $\tau_r = f(h_r)$, the rise time τ_r for each known value of h_r can be found in real time. The ramp command generation scheme is shown in Fig. 3.

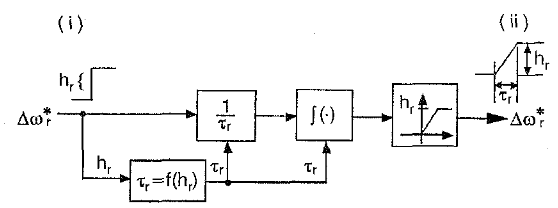

Fig. 3 *Ramp command generation scheme*
(i) Step command; (ii) ramp command

5 A simple model-following controller

As the operating condition is changed, the prescribed drive control specifications may not be further satisfied. In this case, the closed-loop tracking transfer function of the drive controlled by the designed PI-D 2DOF controller in the nominal case is found and used as a reference model $H_{ref}(s)$, since it represents the desired tracking response. From eqn. 12 and Fig. 1 one can find that

$$H_{ref}(s) = H_{dr}(s) = \frac{d_1 s + d_0}{s^2 + 2a_1 s + a_0} \tag{34}$$

A compensation control signal $\delta i_{qs}^*(t) = K_e[\Delta\omega_{ref}(t) - \Delta\omega_r(t)]$ as shown in Fig. 1 is generated by the model-following controller to improve the tracking response at other operating conditions. In addition, the load regulation response can be further improved.

6 Speed control of an induction motor drive

System configuration of motor drive: An indirect field-oriented induction motor drive is shown in Fig. 4 [1, 3], which consists of an induction motor (3-phase 2-pole 5.4A 2000 rev/min), a current-controlled PWM inverter, an indirect field-orientation mechanism and the proposed speed controller (PI-D 2DOFC and model-following controller). A permanent DC generator with load resistance R_L is coupled mechanically to the induction motor shaft to serve as its dynamic load.

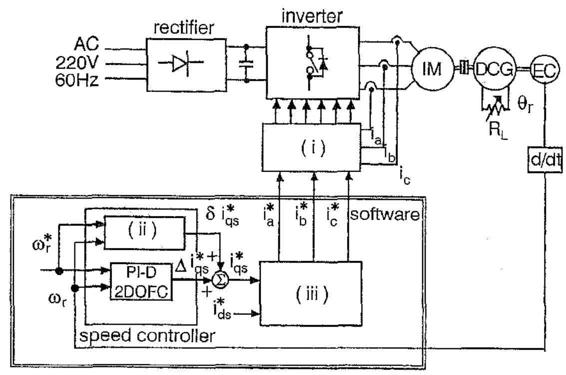

Fig. 4 *Configuration of an indirect field-oriented induction motor drive*
(i) Current-controlled PWM switching scheme; (ii) model-following controller; (iii) indirect field-orientation mechanism

Design of PI-D 2DOF speed controller:
(i) The parameters of the motor drive transfer function at nominal case (ω_{r0} = 1000 rev/min, R_L = 77.6Ω, $i_{qs}^*(0)$ = 1.1067A) are estimated [14] to be: a = 0.567, b = 70.68, K_t = 0.759, $\tau \simeq$ 0.02s. The conversion factor of the speed sensor is $K_{\omega r}$ = 0.00955 and the limit value is I_{limit} = 7A.

(ii) The following control specifications of the step command ($\Delta\omega_r^*$ = 100 rev/min) tracking and step load (ΔT_L = 1Nm) regulation speed responses are specified: (i) t_{re} = 0.2s; (ii) $\Delta\omega_{dm}$ = 15 rev/min; (iii) i_{qsm}^* = 3.5A, $i_{qs}^*(0)$ = 1.1067A, Δi_{qsm}^* = 2.3933A; (iv) overshoot = 0; and (v) steady-state errors of two kinds of responses are zero.

(iii) Neglecting the dead time, one can find the parameters of the proposed PI-D 2DOF controller from eqns. 21–27 using PC-MATLAB, as follows:

$$\begin{aligned}&K_P = 64.0953, \quad K_I = 389.1011, \quad K_D = 0.6363 \\ &c_0 = 150.3371, \quad c_1 = 24.7645 \\ &d_0 = 150.3371, \quad d_1 = 12.2612\end{aligned} \tag{35}$$

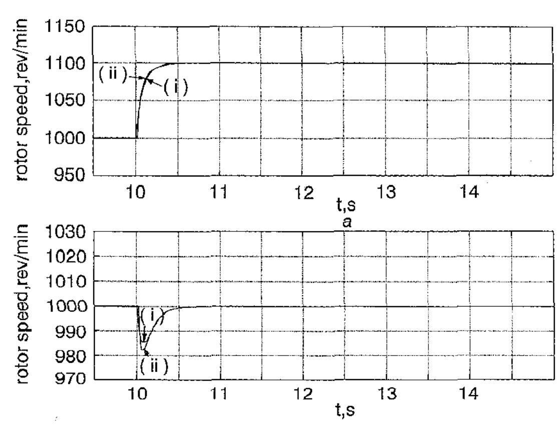

Fig. 5 *Simulated step rotor speed and torque current responses at nominal case*
ω_{r0} = 1000 rev/min, R_L = 77.6Ω
a Command tracking (1000 to 1100 rev/min);
b Load regulation (ΔT_L = 1Nm)
(i) Without and (ii) with transport delay

Simulation results: The simulated results for the nominal case without dead time shown in Figs. 5*a* and *b* indicate that the given specifications are fully satisfied. To observe the effect of transport delay on the control performance, Fig. 5 also shows the responses when the delay $\tau = 0.02$s exists; no significant deviations in the response trajectories are observed in this case from the results. The dead time $\tau = 0.02$s is added in the following simulations.

Now letting $i^*_{qsm} = I_{limit} = 7$ A, $i^*_{qs}(0) = 1.1067$A and $\Delta i^*_{qsm} = 5.8923$A, the ramp speed commands are changed from 1000 to 2000, 1800 and 1500rev/min, respectively, and the command rise times found from eqn. 33 are $\tau_r = 0.3826$s, 0.2862s and 0.1425s. The simulated rotor speed and torque current responses due to the ramp command and step command changes from 1000 to 1500 rev/min are compared in Figs. 6*a* and *b*, which indicate that an overshoot in step response caused by hard control saturation is occurring, but the responses without overshoot and control saturation are obtained by using the proposed ramp command.

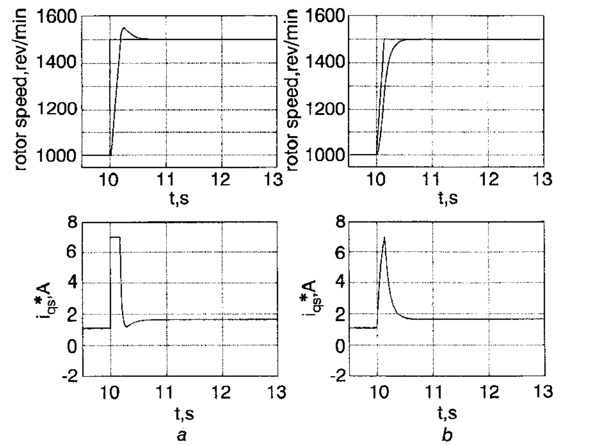

Fig. 6 *Simulated rotor speed and torque current responses due to large command change (1000 to 1500rev/min)*
a Step
b Ramp

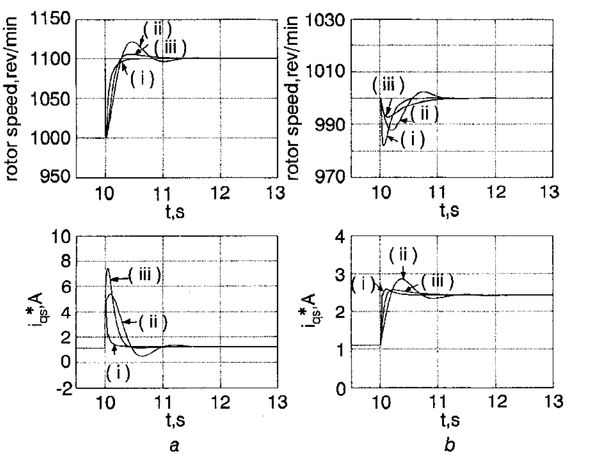

Fig. 7 *Simulated step tracking and regulation responses due to change of load inertia constant*
(i) Nominal case; (ii) $J = 5J_0$, 2DOFC only; (iii) $J = 5J_0$, 2DOFC and model-following controller, $K_e = 90$
a Command tracking (1000 to 1100rev/min)
b Load regulation ($\Delta T_L = 1$ Nm)

Suppose that the inertia constant is changed from $J = J_0$ (nominal value) to $J = 5J_0$; the simulated rotor speed and current responses due to step command change and step load torque change ($\Delta T_L = 1$Nm) by only the PI-D 2DOFC are shown in Figs. 7*a* and *b*. It is observed from the results that the tracking response is significantly deviated from the desired trajectory. Now the model-following controller with $K_e = 90$, which is determined by trial and error, is added. The simulated responses are also plotted in Figs. 7*a* and *b*; the results show that great improvement of responses has been achieved. Further increase in the value of K_e will lead to a significant increase in control force (i^*_{qs}) with only limited further improvement in speed response.

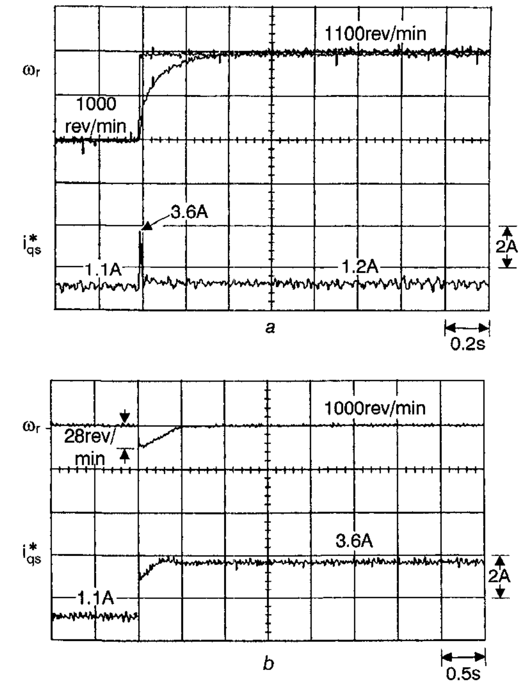

Fig. 8 *Measured rotor speed and current responses at nominal case*
$\omega_{r0} = 1000$ rev/min, $R_L = 77.6\Omega$
a Owing to step command change ($\omega_r = 1000$ to 1100rev/min)
b Owing to step load resistance change ($R_L = 77.6$ to 27.4Ω)

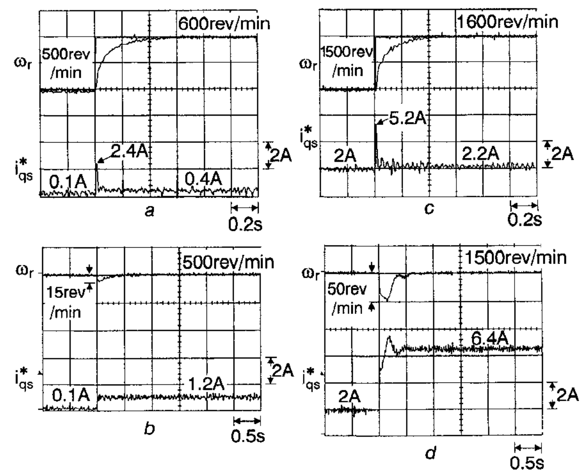

Fig. 9 *Measured rotor speed and current responses at other two cases*
a Step tracking (500 to 600 rev/min, $R_L = 77.6\Omega$)
b Step load resistance change ($\omega_{r0} = 500$rev/min, $R_L = 77.6$ to $27.4\ \Omega$)
c Step tracking (1500 to 1600 rev/min, $R_L = 77.6\Omega$)
d Step load resistance change ($\omega_{r0} = 1500$ rev/min, $R_L = 77.6$ to $27.4\ \Omega$)

Implementation and measured results: The designed PI-D 2DOFC and the model-following controller are transferred into the digital control algorithms and realised using the C-language on a PC 486 based control computer. The measured rotor speed and current responses in the nominal case ($\omega_r = 1000$rev/min, $R_L = 77.6\Omega$) due to step command change ($\omega_r = 1000$ to 1100rev/min) and step load resistance change ($R_L = 77.6$ to 27.4Ω, $\Delta T_L \simeq 1.7$Nm) are plotted in Figs. 8*a* and *b*. The results indicate that the given specifications are roughly satisfied. Good dynamic responses can also be observed from the measured responses at two other operating conditions plotted in Figs. 9*a* – *d*. If the step command is changed from $\omega_r = 1000$ to 1500rev/min, then the response in Fig. 10*a* shows that the overshoot is occurring because of hard saturation in the current. To improve this, the ramp command with rise time $\tau_r = 0.1425$s is applied instead; the response shown in Fig. 10*b* indicates that the overshoot has been eliminated. The measured rotor speed and current responses due to the step command change and step load resistance change (R_L = 77.6 to 27.4Ω) in the nominal case by the designed PI-D 2DOFC and model-following controller (K_e = 90) are shown in Figs. 11*a*, *b*; comparison of the results shown in Figs. 8 and 11 indicate that the regulation speed response is much improved by adding the model-following controller.

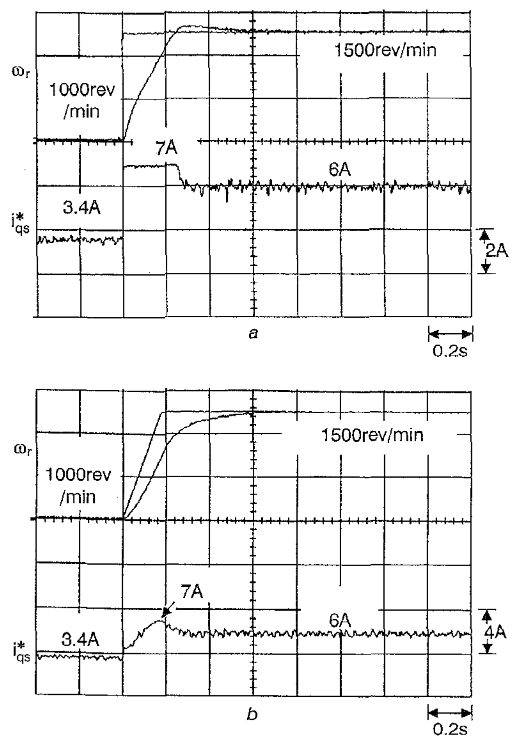

Fig. 10 *Measured responses due to large command change (1000 to 1500 rev/min)*
a Step command
b Proposed ramp command

7 Conclusions

Design and implementation of a PI-D 2DOF controller for motor drives have been presented in this paper. The proposed 2DOF controller consists of a PI-D feedback controller and a command feedforward controller to handle the tracking and regulation speed control problems. The controller parameters can be found systematically to meet the given motor drive specifications. In the design stage, the effects of control effort and change rate of ramp command are also considered. As the operation condition changes occur, a model-following controller is added to preserve the control specifications. The effectiveness of the proposed controller has been confirmed by some simulation and experimental results of an indirect field-oriented induction motor drive.

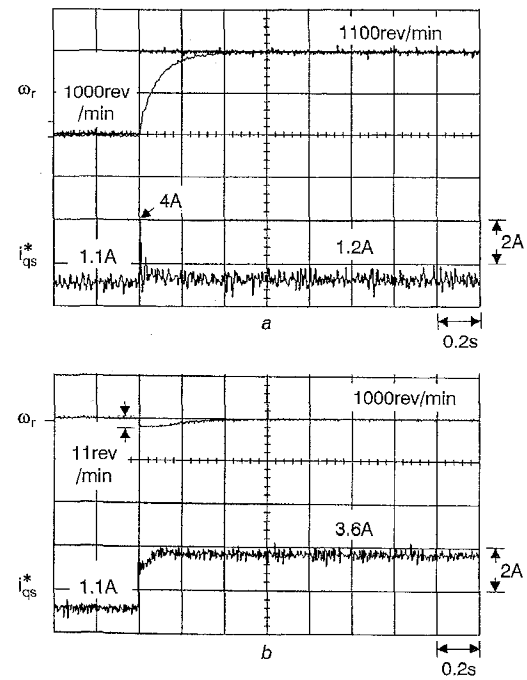

Fig. 11 *Measured rotor speed and current responses at nominal case by PI-D 2DOFC and model-following controller (K_e =90)*
a Owing to step command change
b Owing to step load resistance change (R_L = 77.6 to 27.4Ω)

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