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Uniform Pulse-Width Modulation (UPWM) Three-Phase Four-Quadrant ac-dc Converter-Fed DC Motor Drive

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Abstract: A three-phase ac-dc GTO thyristor converter-fed dc motor is studied in detail, employing an Uniform Pulse-Width Modulation (UPWM) scheme and verified by computer simulation. It has been found to offer good performance. It offers only two-quadrant operation because of the unidirectional current conduction nature of GTO's. A four-quadrant converter that employs a single six-GTO bridge converter and four thyristors serving as a reversing switch is described. The four-quadrant dc drive employing the proposed converter and the control structure including speed and current control loop is also presented. Simulation results with a separately excited dc motor are given for steady-state and transient responses of the drive. The simulation results are shown to be in good agreement with the theory.

Key words: GTO, ac-dc converter, pulse with modulation, UPWM, DC drive

INTRODUCTION

Three-phase ac-to-dc converters find application in speed control of dc motors. They are ideal electronic actuators for DC drives because of their virtually unlimited output power and excellent controllability. The speed response is usually adequate to handle the electromechanical transients occurring in drives[1]. The phase delay control technique is extensively used in dc power conditioning systems since they do not require any special means of commutation. The thyristor converters employing phase control have disadvantages of having harmonics in the source current and poor power factor, particularly at low-output voltages. When it is used for dc motor control, the armature current ripple increases losses, derates the motor and causes discontinuous conduction, which increases speed regulation and slows down the transient response at light loads[2]. Forced-commutated converters with Pulse Width Modulation (PWM) control have been developed and offer considerable performance improvements over phase-controlled converters. It makes the fundamental power factor unity the ripple of the load current and the zone of discontinuous conduction operation are reduced when compared to conventional converters. The increasing availability and power capability of controlled-on and controlled-off power switching devices, such as gate turn-off thyristors (GTO's), Insulated Gate Bipolar Transistors (IGBT's) and MOS-Controlled Thyristors (MCT's), are expected to reinforce self-commutated ac-dc converters with PWM control strategy to replace the conventional phase-controlled converters within the available power ratings. The flexibility to operate with variable chopping frequency is an additional merit of self-commutated PWM converters[3]. A three-phase PWM GTO converter -fed dc motor drive offers only two-quadrant operation because of the unidirectional current conduction nature of GTO's. A dual-converter is realized by employing two converters connected in antiparallel across the load, Allows operation in all four quadrants. The present study describes a four-quadrant converter that employs a single six-GTO bridge converter and four thyristors serving as a reversing switch. This allows substantial reduction in cost because GTO's are quite expensive compared to thyristors. The reduction in cost, however, is obtained at the expense of increase in losses and lower efficiency due to two extra devices in armature circuit at all times[2]. In this paper, the performance characteristics of the uniform pulse width modulated three-phase four-quadrant ac-dc converter-fed dc motor drive are evaluated. An ac-dc GTO thyristor converter is analyzed, employing UPWM. Pulse width control strategy is employed in the normal operation of the converter either as a rectifier or an inverter. A four-quadrant dc drive employing the proposed converter and closed-loop speed control with inner current control loop is also presented. Simulation results with a separately excited dc motor are given for

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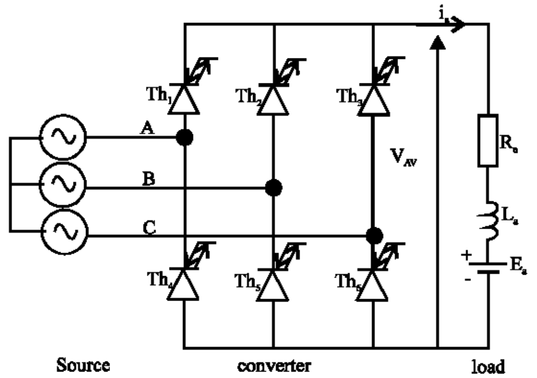


Fig. 1: Three-phase PWM ac-dc converter

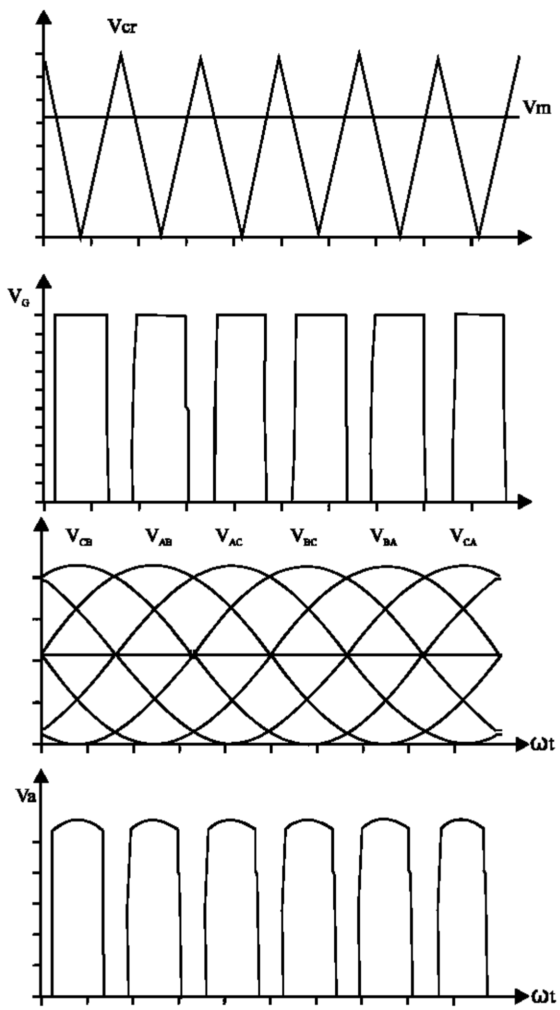


Fig. 2: Principle of UPWM control strategy

steady-state and transient responses of the drive. The simulation results are shown to be in good agreement with the theory.

Principle of operation: Figure 1 shows the power circuit configuration of a three phase ac-dc converter supplying an active load such as a dc motor. The source impedance is neglected. The power semiconductor switches, Operating in chopping mode, are used to vary amplitude of the average output voltage. if thyristors were employed, they must be force commutated On the other hand, if power transistors, MOSFET's, IGBT's, IGCT'or GTO's were employed; they are self-commutated without any need for forced commutation[2]. Although a GTO thyristor is employed as Fig. 1 shows. Uniform PWM (UPWM) control strategy is used in order to control the output voltage. The Principe of this control strategy is demonstrated in Fig. 2. The carrier wave V_{cr} is compared with a variable time independent dc control voltage V_m to generate the drive signal V_g of the switching devices.The supply source is connected to the load during the interval when V_m is greater than V_{cr}. The frequency fp of the carrier signal depends on the number of output voltage pulses P desired in one cycle of the ac supply voltage. The switching-on and switching-off times of the switching devices for the K_{th} pulse are given as:

$$t_{kon} = \frac{t_p}{2}(2.k - 1 - m)$$

$$t_{koff} = \frac{t_p}{2}(2.k - 1 + m)$$

The output period of the carrier wave is given by:

$$t_p = \frac{2\pi}{p} = \frac{1}{f_p}$$

Where:

P =6, 12, 18, 24, 30………
k = 1, 2, 3,……,p.

The average output voltage of the converter is determined by the modulation index m, which for the UPWM control strategy, is varied by the control circuitry in the range ($0 \le m \le 1$), m is given as:

$$m = \frac{V_{mm}}{V_{crm}}.$$

The expression for the corresponding modulating signal, switching-on angles α's and switching-off angles β's for the K_{th} pulse in a supply cycle are given as:

$$\alpha_k = \frac{\pi}{p}(2k - 1 - m)$$

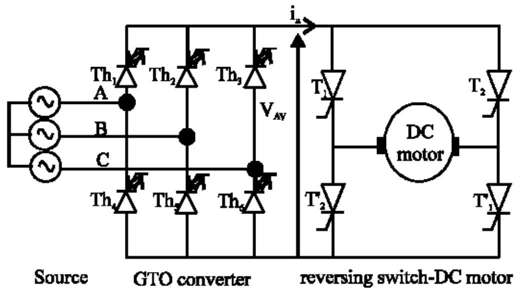


Fig. 3: Four-quadrant operation of a DC drive by a static reversing switch

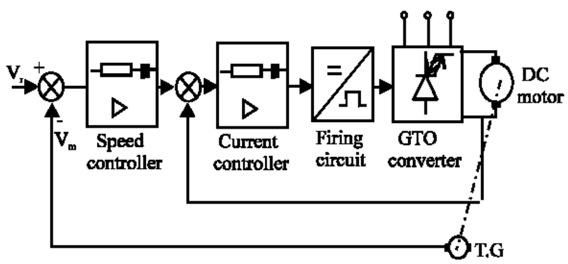


Fig. 4: General schematic of closed-loop speed control

$$\beta_k = \frac{\pi}{p}(2k - 1 + m)$$

Output voltage: With reference to Fig. 2, the expression for the average output voltage V_{av} du to P number of pulses is:

$$V_{av} = \frac{3\sqrt{6}.V_s}{2.\pi} \sum_{i=1}^{p/3} \int_{\pi/6+\alpha_i}^{\pi/6+\beta_i} \sin(\omega t + \theta r) d(\omega t)$$

$$V_{av} = \frac{3\sqrt{2}\,V_s}{\pi} \sum_{i=1}^{p/3} \left[\cos(\alpha_i + \frac{\pi}{3}) - \cos(\beta_i + \frac{\pi}{3}) \right]$$

Output current: The expression for the armature current during the i_{th} voltage pulse is given as:

$$ia = I_P \sin(\omega t - \phi + \frac{\pi}{3}) - I_E$$

$$+ \left[I_{\alpha i} + \frac{E_a}{R_a} - I_P \sin(\alpha_i - \phi + \frac{\pi}{3}) \right] e^{\frac{Ra}{La\omega}(\alpha_i - \omega t)}$$

$$\alpha_i \le \omega t \le \beta_i$$

$$ia = -\frac{E_a}{R_a} + [I_P \sin(\beta_i - \phi + \frac{\pi}{3})$$

$$+ (I_{\alpha i} + \frac{E_a}{R_a} - I_P \sin(\alpha_i - \phi + \frac{\pi}{3}))e^{\frac{Ra}{La\omega}(\alpha_i - \beta_i)}]e^{\frac{Ra}{La\omega}(\beta_i - \omega t)}$$

$$\beta_i \le \omega t \le \alpha_{i+1}$$

The proposed four-quadrant converter: The converter power circuit with a dc motor load is shown in Fig. 3. The GTO converter employs a six-GTO bridge converter. This two-quadrant GTO converter is operated with uniform PWM to produce 12 output voltage pulses during a cycle of the ac source voltage. The principle of armature reversal is realised in Fig. 3 with the help of static reversing switch that consists of four reversing thyristors.

Thyristor pair (T_1 ,T'_1) are continuously made conducting for positive direction of motor current while the other are blocked. When zero current is reached, the opposite pair of thyristors (T_2 ,T'_2) can be fired in order to reverse the polarity of the armature current.

Control structure of drive: The schematic block diagram of speed control scheme is given in Fig. 4.

The block diagram is shown in Fig. 5 the transfer function of each block is given below.

The schematic diagram of the closed loop speed control scheme is shown in Fig. 5. It employs an inner-current control loop within the speed loop. The speed controller out put, which forms the current reference for the current controller is clamped to provide a current-limiting feature.

Dc motor: The equivalent circuit of the separately excited dc motor coupled to a separately excited dc generator for the purpose of loading can be represented in schematic form by Fig. 6. Assuming constant field excitation, the equations are:

$$V_a = R_a.i_a + L_a.di_a/dt + E_a \quad (1)$$

$$m_M = J\frac{d\omega_m}{dt} + m_L \quad (2)$$

$$E_a = K_m.\omega_m \quad (3)$$

$$m_M = K_m.ia \quad (4)$$

Taking LaPlace transform of (1)-(4) and rearranging the terms, the following equations can be obtained:

$$I_a = \frac{V_a(s) - K_m.\omega_m(s)}{R_a(1 + T_a.S)}$$

$$\omega_m = \frac{K_m.I_a(s) - m_L(s)}{J.S} \quad (6)$$

$$\omega_m = \frac{m_M(s) - m_L(s)}{J.S}$$

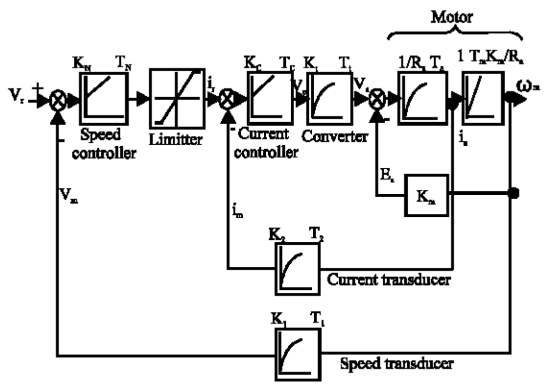


Fig. 5: Control structure of drive including speed and current control loop

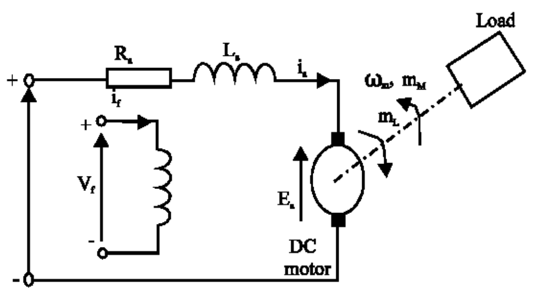


Fig. 6: Equivalent circuit of dc motor-load system

The dynamic system, described by equations (6), is represented as a block diagram in Fig. 7.

As a constant field dc generator connected to a fixed resistance forms the load on the motor shaft, the load torque varies linearly with the speed. The equation is

$$m_L = B \cdot \omega_m \tag{7}$$

Converter: The secondary voltage of the power transformer is chosen in such a way that for the control voltage $V_c = 0.9\ V_c\max$, the converter voltage is equal to the rated voltage of the dc motor. The control voltage varies from - 5 to + 5V. Gain K_t of the converter (including the firing circuit) is given as the ratio of the maximum value of desired output voltage to the change in control voltage V_c required to vary the output voltage from 0 to V_c max[4]. The time delay of the converter is approximated by first-order time constant T_t which is equal to half the interval between two consecutive voltage pulses.

Thus,

$$T_t = 1/2.20/6\text{ms} \quad \text{for } P = 6$$

And

$$T_t = 1/2.20/12\text{ms} \quad \text{for } P = 12$$

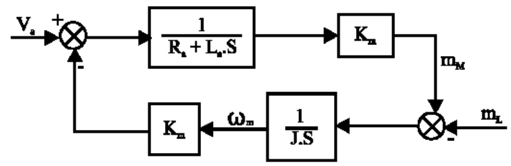


Fig. 7: Block diagram of motor-load system

The transfer function of the converter can be written as:

$$\frac{V_a(s)}{V_c(s)} = \frac{K_t}{1+T_t.S} \tag{8}$$

Current transducer: A signal proportional to the armature current is obtained by using a small resistance in series with the armature circuit. The feedback signal derived from the current transducer is passed through an RC filter with a time constant T_2 in order to reduce the ripple in the current signal. Thus, the transfer function of the current transducer with the filter is written as:

$$\frac{I_m(s)}{I_a(s)} = \frac{K_2}{1+T_2.S} \tag{9}$$

Speed transducer: A tacho-generator is used to get the speed signal. Since a 5V dc signal corresponds to the rated speed (1500 r/min).An RC filter with a time constant T_1 is used to smooth out the spikes in the speed signal. The transfer function of the speed transducer with the filter is given as[4]:

$$\frac{V_m(s)}{\omega_m(s)} = \frac{K_1}{1+T_1.S} \tag{10}$$

SIMULATION RESULTS

The source voltage; the motor armature voltage and current waveforms for motoring and regenerating (for rectification and inversion) operation, are shown in Fig. 8 and 9, respectively. The waveforms of the developed torque and the motor speed for a different number of pulses P (P=6 and P=12) are shown in Fig. 10, load is applied at t=1s. The ripples in the developed torque were observed. There is an improvement in performance with an increase in the pulse number. Four-quadrant drive ability is demonstrated in Fig. 11 and 12 the former shows the speed response for a speed reversal command

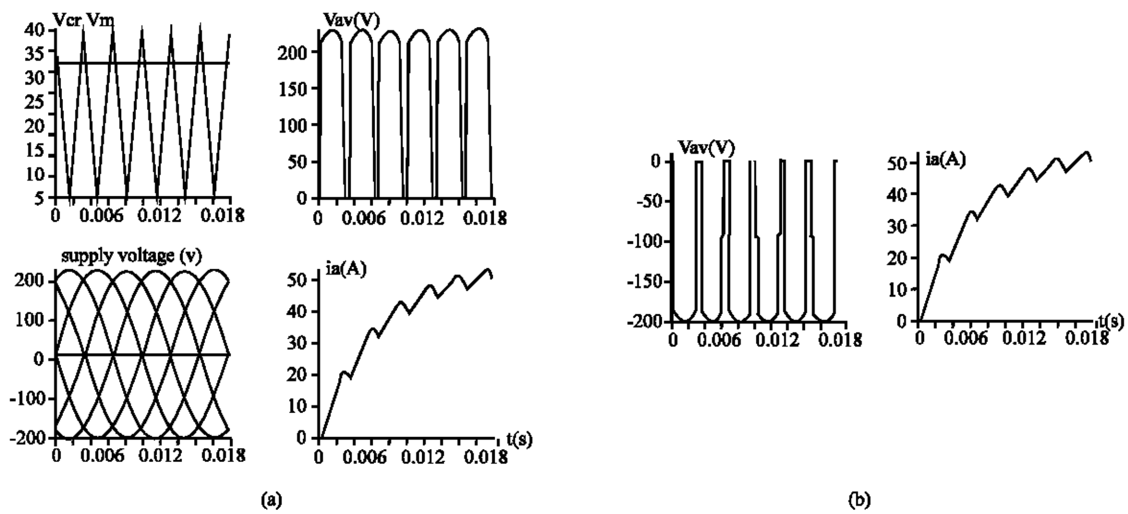


Fig. 8: Simulated waveforms of output voltage and load current through UPWM GTO converter (a) for motoring operation (p=6, m=0.8). (b) for regenerating operation (p=6, m=0.8)

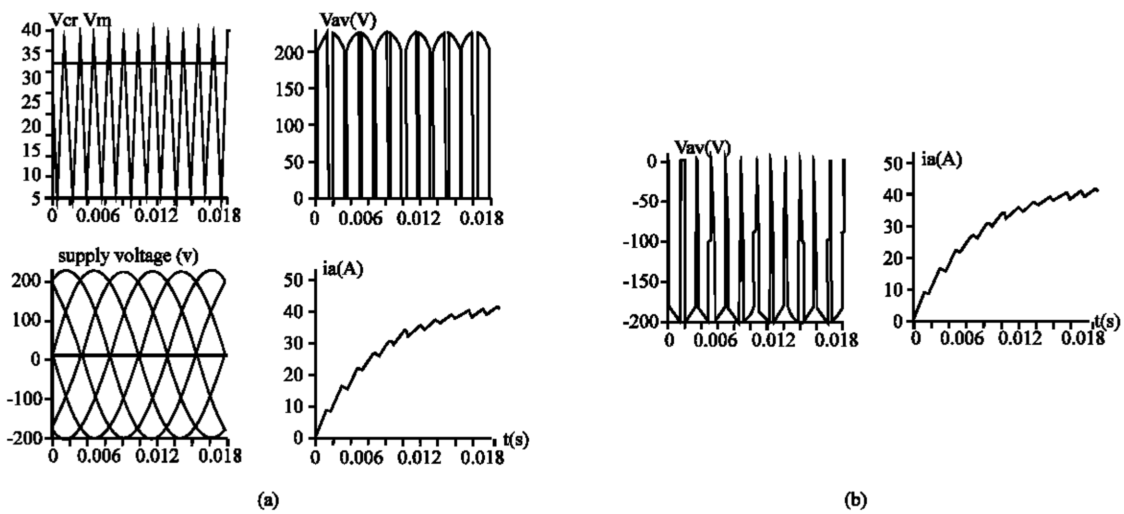


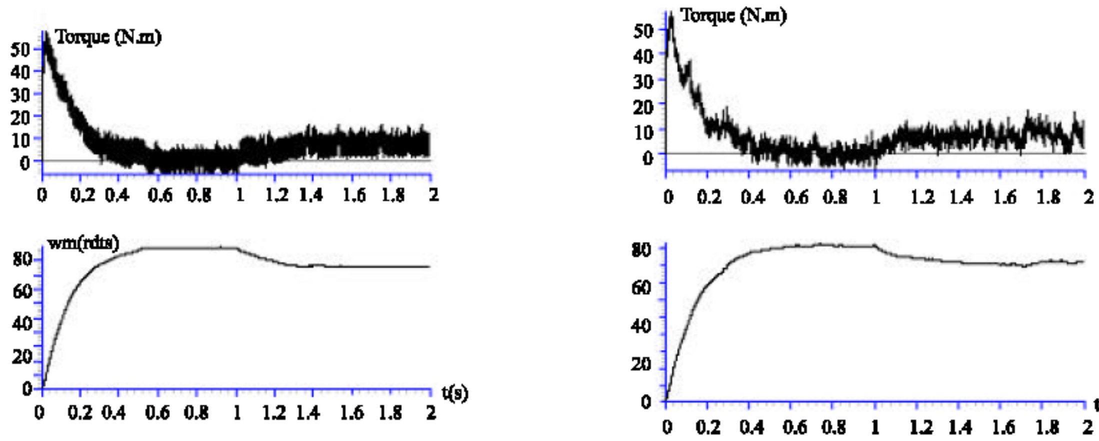
Fig. 9: Simulated waveforms of output voltage and load current through UPWM GTO converter (a) for motoring operation (p=12, m=0.8). (b) for regenerating operation (p=12, m=0.8)

from +1500 to -1500 r/min. As the speed reversal is initiated, the armature current quickly reverses through the static reversing switch. The motor decelerates to standstill as the converter operates as an inverter feeding power back the ac source. The motor is then accelerates fast in the reverse direction and the speed settles down to the desired value.

Figure 12 shows the speed response for control voltage varies from -5 to +5v with a load torque m_L=constant. The armature current reverses though the reversing switch the motor is decelerated quickly. When desired speed is reaches, the current is again set back in previous direction (these corresponding for operating in a four quadrant drive).

CONCLUSION

The comparative study of pulse width modulation scheme for an ac-dc PWM converter shows that the Uniform Pulse Width Modulation Scheme (UPWM) offers good performance. Simulation results show that the control strategy can be applied to both rectifying and regenerating modes of operation. A four-quadrant dc drive employing the proposed converter and closed-loop



(a) (b)

Fig. 10: Response of tirque and speed of UPWM ac-dc converter-fed dc motor. (A) when (p=6, m=0.6). (b) when (p=12, m=0.6)

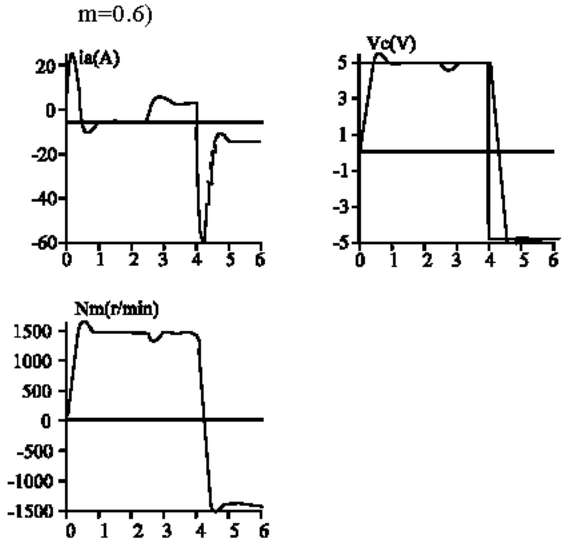


Fig. 11: Speed and toreque response for reversal of speed command from 1500 to -1500 r/min of closed loop scheme. When $m_L = B.\omega_m$

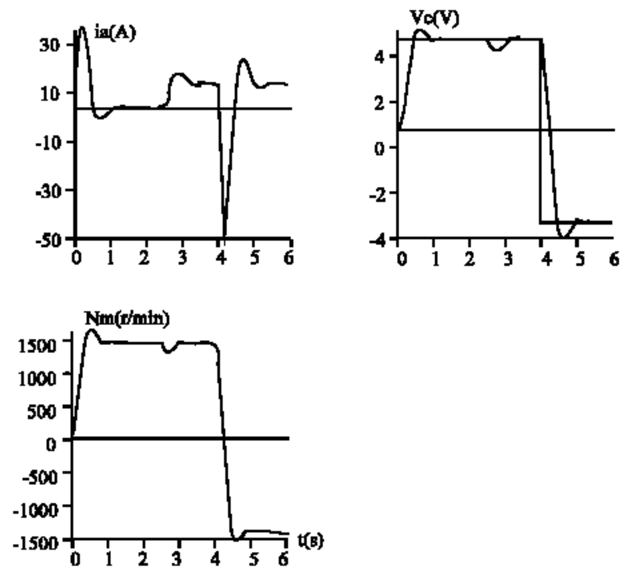


Fig. 12: Speed and toreque response for reversal of speed command from 1500 to -1500 r/min of closed loop scheme. When m_L = constant

speed control with inner current control loop has been described and verified by computer simulation. The simulation results are shown to be in good agreement with the theoretical observations.

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