VECTOR CONTROLLED-INDUCTION MOTOR DRIVE: OPERATION AND ANALYSIS

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Abstract

Many industrial applications require a continuously adjustable range of speeds. DC motors have been used in such drives. However, DC motors are expensive, prohibitive in hazardous atmospheres and require frequent commutators and brushes maintenance. Induction Motors (IM's), on the other hand, are cheap, rugged, have no commutators, and are suitable for high-speed applications but they exhibit highly coupled nonlinear multi-variable structures. The availability of solid-state controllers, although more complex than those used for DC motors, has made it possible to drive induction motors in the same way as a separately excited DC motor using vector control scheme where torque control is achieved by controlling the torque and flux current components of the armature current independently. Vector control has a fast torque response which allows accurate torque, speed or position control and it can operate the induction motor in a four-quadrant mode. Also, decoupled flux and torque control allows operating induction machine with a low load torque. This paper presents the operation and analysis of the indirect-vector controlled induction motor drive. The basic principle of vector control induction motor is presented. The dynamic model is explained. The effect of torque and flux producing components of stator current on steady state performance is studied. The transient response of vector controlled induction motor is analyzed and then compared with that of the DC machine to show analogy between both drives. The reversal of speed direction and field weakening operation are explained. A comparison between vector controlled induction motor and chopped dc drives are compared.

List of symbols

V^e_{ds}, V^e_{qs} : steady state synchronous frame d-q stator voltages, V
I^e_{ds} , I^e_{qs} : steady state synchronous frame d-q stator currents, A
I^e_{dr} , I^e_{qr} : steady state synchronous frame d-q rotor currents, A
v^e_{ds}, v^e_{qs} : instantaneous synchronous frame d-q stator voltages, V
i^e_{ds} , i^e_{qs} : instantaneous synchronous frame d-q stator currents, A
i^e_{dr} , i^e_{qr} : instantaneous synchronous frame d-q rotor currents, A
v^s_{ds}, v^s_{qs} : instantaneous stationary frame d-q stator voltages, V
i^s_{ds} , i^s_{qs} : instantaneous stationary frame d-q stator currents, A

ψ^e_{ds}, ψ^e_{qs} : synchronous frame d- and q- stator flux linkages, wb

ψ^e_{dr}, ψ^e_{qr} : synchronous frame d- and q- rotor flux linkages, wb

T_e , T_L : load and electromagnetic torque, Nm

ω_e, ω_{sl} : synchronous and slip speed, rad/sec

ω_r, ω_r* : actual and command rotor speed, rad/sec

P : No. of poles

1. Introduction

DC and induction motors have served industrial applications that require variable speed rotating shafts. DC machines have traditionally dominated most of drive systems. Although the machine is more expensive, the control principles and converter equipment required are somewhat simpler. Their main drawback is the presence of commutators and brushes, which results in a necessity for frequent maintenance. Induction machines, on the other hand, are rugged and less expensive, and they have been favored for almost all constant speed drive applications. However, their use as a variable speed drive has been dramatically complex, since the equipments needed are very expensive and suffer from huge complexities in design and implementation. AC drives generally require more complicated control algorithms implemented by fast real time signal processing. The efficiency of the speed control operation is rather low compared to the encountered difficulties. Recent advancements in power electronics and microcomputers have made it possible to implement sophisticated control tasks at reasonable cost. Therefore, induction machine drive became a viable alternative to DC drives in many applications, such as robotics, machine tools and rolling mills, where fast dynamic response, parameter insensitive control characteristics and rapid recovery from speed drop caused by impact loads are required. The vector control method has several disadvantages such as the cost of the required two current sensors and the rotor speed sensor.

2. Speed control of IM

An induction motor is essentially a constant-speed motor, close to synchronous speed, when connected to a constant-voltage and constant-frequency power supply. A simple and economic method of induction motor control is to vary its stator voltage at the fixed supply frequency using triacs (Mohan, Undekand and W. Robbins, 1989). This is characterized by a low value of starting torque and a poor dynamic and static performance. In order to generate the highest possible torque per ampere of stator current, and hence the best possible utilization of the available current capability of the drive, the machine flux level must be kept constant and closed to its nominal value as the motor operating conditions vary. Indirect flux regulation schemes such as the "volt/hertz" control and the "slip/current" control have been extensively used in industry (Hughes, Corda, and

Andrade, 1993) but they fail to provide satisfactory transient performance. Highest possible control performance from an induction machine is obtained using vector control or field oriented control (Bose, 1986), where the stator current or voltage space phasors are controlled in magnitude and position.

3. Fundamentals of vector control IM

The scalar control relates only to the magnitude control of a variable. In vector control, both magnitude and phase of a vector are controlled, where an independent or decoupled control of flux and torque of the motor is performed such that, each of the flux and torque control loops contribute in order to regulate both of the magnitude and frequency of the stator voltage that means the machine is controlled like a separately excited DC motor whose armature and filed currents are orthogonal or de-coupled vectors where the field current is set to maintain the rated field flux, and torque is changed by changing the armature current. Therefore the torque sensitivity remains maximum in both transient and steady state operations. If the induction motor is considered in a synchronously rotating reference frame, where the sinusoidal variables appear as DC quantities at steady state, the direct and quadrature components of the stator current in synchronously rotating reference frame are analogous similar to the field current and armature currents of the DC motor (Vas, 1992). With the indirect method of vector control, the flux position is calculated by first calculating the slip speed, giving the speed of the flux relative to the rotor speed. The slip speed is then integrated, giving the slip angle, or the angle of flux relative to the rotor position. The rotor position is either measured using a shaft position encoder, or calculated by integrating the measured rotor speed. The rotor angle is added to the slip angle to give the position of the flux relative to the stator. The calculated flux angle is used to perform the transformations between stationary and synchronous reference frames. By using a twin-axis synchronously rotating reference frame aligned with the flux vector, the stator current can be split up into a flux producing component and a torque-producing component, both of which are DC values at steady-state conditions which allows decoupled control of flux and torque. The flux producing current component (*d*-axis) provides a slow response mechanism to change the flux in the machine. The torque producing current component (*q*-axis) allows fast controlled changes of torque (Bose, Simoes, Cerceluis, Rajashekara and Martin, 1995). So, the control dynamics become decoupled since the active and reactive components of current are perpendicular and have no mutual effects. Several methods have been proposed to implement field-oriented control. Basically, the schemes can be classified into direct (Blaschke, 1972) and indirect (Hasse, 1969) methods. The difference between these two methods lies in the way that rotor flux magnitude and position are calculated. In the direct method, the rotor flux is measured using search coils or Hall-effect sensors built into the air gap of the machine at the time of manufacture, or the flux is calculated using a flux model of the machine. Due to the difficulty in obtaining accurate estimates flux at low speed, the direct method of vector control is normally limited to operating at speed greater than 10% of the base speed, unless the flux is calculated using rotor speed measurement and stator current (Vas, 1992). In the indirect method of vector control, the slip angle which is defined as the difference between the rotor and the synchronous angle, is calculated using the measured stator current and rotor speed, giving the position of the rotor flux-linkage when added to the rotor angle. This method heavily depends on the rotor time constant. It avoids the requirement of flux acquisition by using known motor parameters to compute the appropriate motor slip frequency to obtain the desired flux position (Wade, 1995). Vector control gives a fast torque response and a wide possible speed control range from near zero speed to over the maximum rated speed without exceeding the motor's rated voltage, current or power, in either direction, including motoring or regenerating operation. Also, field-weakening operation, with proportionally less than rated torque, is available as the speed is increased above rated speed. The disadvantages of vector control are the requirements for a shaft speed sensor and current transducers on the stator. A power inverter with a fast switching speed, is required. Vector control is also relatively complex mathematically, requiring a fast microprocessor or digital signal processor for implementation. Also, the machine parameters have to be known accurately.

4. Basic principal and dynamic model

The dynamic model of the vector controlled IM can be concluded as follows. The rotor voltages are expressed as (Hughes, Corda, and Andrade, 1993):

$$0 = R_r i^e{}_{dr} + \frac{d\psi^e{}_{dr}}{dt} + (\omega_e - \omega_r)\psi^e{}_{qr} \tag{1}$$

$$0 = R_r i^e{}_{qr} + \frac{d\psi^e{}_{qr}}{dt} - (\omega_e - \omega_r)\psi^e{}_{dr} \tag{2}$$

$$v^e{}_{ds} = R_s i^e{}_{ds} + \frac{d\psi^e{}_{ds}}{dt} + \omega_e \psi^e{}_{qs} \tag{3}$$

$$v^e{}_{qs} = R_s i^e{}_{qs} + \frac{d\psi^e{}_{qs}}{dt} - \omega_e \psi^e{}_{ds} \tag{4}$$

The flux linkages are given by:

$$\psi^e{}_{ds} = L_s i^e{}_{ds} + L_m i^e{}_{dr} \tag{5}$$

$$\psi^e{}_{qs} = L_s i^e{}_{qs} + L_m i^e{}_{qr} \tag{6}$$

$$\psi^e{}_{dr} = L_r i^e{}_{dr} + L_m i^e{}_{ds} \tag{7}$$

$$\psi^e{}_{qr} = L_r i^e{}_{qr} + L_m i^e{}_{qs} \tag{8}$$

By aligning the d^e–axis with the rotor flux instead of the air-gap flux, the rotor flux in the q^e–axis must be zero. Hence,

$$\psi^e{}_{qr} = \frac{d\psi^e{}_{qr}}{dt} = 0 \tag{9}$$

This implies that:

$$\psi^e{}_{dr} = (say)\psi_r = constant \tag{10}$$

Substituting (9) and (10) into (1) and (7) and rearranging to get:

$$\frac{L_r}{R_r}\frac{d\psi_r}{dt} + \psi_r = L_m i^e{}_{ds} \tag{11}$$

Taking Lapalce transform for (11), the transfer function G(s) can be expressed as follows:

$$G(s) = \frac{\psi_r(s)}{i^e{}_{ds}(s)} = \frac{L_m}{\frac{L_r}{R_r}s + 1} \tag{12}$$

Also, the slip speed can be calculated by subsisting (9) and (10) into (2) and (8) and rearranging as follows:

$$\omega_{sl} = \omega_e - \omega_r = \frac{i^e_{qs}}{\psi_r}\left(\frac{L_m R_r}{L_r}\right) \tag{13}$$

Substituting vector control condition in the torque expression in (Boleda and Nassar, 1992) results in:

$$T_e = (\frac{3}{2})(\frac{P}{2})\frac{L_m}{L_r}\psi_r i^e{}_{qs} \tag{14}$$

Eqn. (12) shows that flux level control is achieved by controlling direct component of stator current and (14) shows that torque control is achieved by controlling both direct and quadrature components of stator current. Fig. 1 explains the indirect voltage vector control implementation. After being measured, the three phase currents are converted into stationary frame d^s-q^s stator currents ($i^s{}_{ds}$, $i^s{}_{qs}$) and then to synchronously rotating frame d^e-q^e stator currents ($i^e{}_{ds}$, $i^e{}_{qs}$) using the absolute flux position (θ_e). The two command currents ($i^e{}_{ds}{}^*$, $i^e{}_{qs}{}^*$) are compared with the actual currents ($i^e{}_{ds}$, $i^e{}_{qs}$) and the errors are implemented to the current controllers whose outputs are the synchronously rotating frame d^e-q^e stator voltages ($v^e{}_{ds}$, $v^e{}_{qs}$) which in turn are converted into three phase reference voltages using the absolute flux position. The inverter determines the three phase PWM voltages applied to the motor. Also, the current $i^e{}_{ds}$ is inputted to the transfer function, G(s), given in (12) to calculate the flux ψ_r. The slip speed, which is calculated as given in (13), is added to the rotor speed to find the synchronous speed, ω_e.

5. Steady state analysis

At steady state, rate of change of flux equals zero. Also, for vector control, the flux ψ^e_{qr} equals zero. By substituting these conditions into IM d-q model given in (1) to (4) to get:

$$0 = R_r I^e_{dr} \tag{15}$$

$$0 = R_r I^e_{qr} - (\omega_e - \omega_r)\psi^e_{dr} \tag{16}$$

$$V^e_{ds} = R_r I^e_{dr} + \omega_e \psi^e_{qr} \tag{17}$$

$$V^e_{qs} = R_r I^e_{qr} - \omega_e \psi^e_{dr} \tag{18}$$

Eqn (15) denotes that the current I^e_{dr} equals zero. By applying the condition of the vector control in (6), it is found that:

$$I^e_{qs} = -\frac{L_r}{L_m} I^e_{qr} \tag{19}$$

Where the term $\frac{L_r}{L_m}$ is the turn's ratio of the current in the q-axis. Also by substituting (5) and (6) into (3) and (4) respectively, the steady state equations tend be:

$$V^e_{ds} = R_s I^e_{dr} + \omega_e I^e_{qs}\left(L_s - \frac{L_m^2}{L_r}\right) \tag{20}$$

$$V^e_{qs} = R_s I^e_{qs} - \omega_e I^e_{ds} L_s \tag{21}$$

$$\psi^e_{dr} = L_m I^e_{ds} \tag{22}$$

$$\omega_{sl} = -\frac{I^e_{qs}}{\psi^e_{dr}}\left(\frac{L_m R_r}{L_r}\right) \tag{23}$$

Substituting (22) into (14), the electromagnetic torque equation is given by:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m^2}{L_r} I^e_{ds} I^e_{qs} \tag{24}$$

Equations (15) to (24) help to predict a steady operating point and to plot motor characteristic curves versus speed as follows.

5.1 Effect of load torque on steady state performance.

Steady state performance versus rotor speed is shown in fig. 2, for two different load torques, while keeping the command current I^e_{ds} constant to keep the flux constant at rated value. It is concluded that:

- Rotor flux, which is aligned with d^e-axis, is constant independent on ω_r nor load torque, since the *d*-axis synchronous frame stator current is kept constant.

- Q-axis synchronous frame stator current, I^e_{qs} increased when torque is increased independent on ω_r as long as I^e_{ds} is constant meaning that the current, I^e_{qs} is the torque-producing component of the stator current.
- Slip speed, ω_{sl} increased when torque is increased because ω_{sl} depends on both I^e_{qs}, which is torque dependent, and ψ_r, which is constant, independent on ω_r.
- Synchronous speed ω_e increases as the torque T_L or the speed ω_r increases where the speed ω_e is the sum of ω_r and ω_{sl} which increases when T_L.
- Voltage V^e_{ds} increases with the increase of speed ω_e and current I^e_{qs} as seen from (20). This voltage is analogous to field voltage in DC motor but they do not behave in the same way where voltage of DC motor is only dependent on field producing current, while the voltage V^e_{ds} is dependent on both torque and field producing currents.
- From (21), it is concluded that the increase of current I^e_{qs} and consequently the positive term (R_s I^e_{qs}) is more dominant than the increase of speed ω_e and consequently the negative term L_s ω_e I^e_{ds} which causes the increase of V^e_{qs}. This voltage is analogous to armature voltage in DC motor where both voltages depend on both torque and field producing currents.

5.2 Effect of d- axis command current on steady state performance

Fig. 3 shows steady state performance when speed varies, while keeping load torque constant, for two different operating command currents I^e_{ds}. It is concluded that:

- Current I^e_{qs} decreases when current I^e_{ds} increases, to maintain constant load torque T_L independent on ω_r.
- Rotor flux increases when current I^e_{ds} increases meaning that I^e_{ds} is the flux-producing component of stator current, independent on ω_r.
- The slip speed ω_{sl} decreases independent on ω_r where ω_{sl} depends on I^e_{qs} and ψ^e_{dr}. The increase of I^e_{ds}, and consequently the flux ψ_r, with the decrease of I^e_{qs}, leads to the decrease of ω_{sl}
- As I^e_{ds} increases, ω_{sl} decreases and consequently the synchronous speed ω_e since it is the sum of ω_r and ω_{sl}.
- From (20), it is concluded that the decrease of ω_e and I^e_{qs}, is more dominant than the increase of I^e_{ds} which causes the decrease of V^e_{ds}.
- From (21), it is concluded that the increase of I^e_{ds} is more dominant than the decrease of I^e_{qs}, which causes the increase of V^e_{qs}.

6. Transient Response

To show the analogy between the performance of a vector controlled induction motor and chopper controlled separately excited DC motor having the same power rating, the transient response of the two drives are compared. Fig 4 shows the connection diagram of the DC motor drive where the armature and the field are supplied from a DC supply via a class-E and class-A chopper respectively. The dynamic model of the separately exited DC motor is illustrated in (Mohan, Undekand and W. Robbins, 1989) while the model derived in section (4) is used for the vector controlled induction motor. Fig. 5 and fig. 6 show the performance of the DC motor (to the left) and the vector controlled induction motor (to the right) for both a step command speed while keeping constant load torque and for step command load torque while keeping constant speed command signal, respectively. It is concluded that the vector controlled IM behaves with the same manner as the DC motor drive. The q-axis synchronous current I^e_{qs} and d-axis synchronous current I^e_{ds} in the IM are analogous to the armature current, I_a and field current I_f in the DC motor, respectively such that when the command torque increases while keeping speed command constant, both I^e_{qs} and I_a increase because they are the torque producing currents. Also, when the command speed increases while keeping load torque constant, both I^e_{ds} and I_f remain constant while the voltages V^e_{qs} and V_a increase to increase back EMF across the machines.

Fig. 7 and fig. 8 show the waveform of the IM armature current for each case. For step speed command, it is seen that current magnitude does not change because load torque does not change while current frequency is increased because the synchronous speed increased (Sen,1990). For step load torque, the peak value of the sinusoidal phase-a-current, will increase, while its frequency remain constant. Fig. 7 and 8 prove that vector control of induction motor controls magnitude and position of armature current.

7. Braking and reversal of rotation

The speed direction of the induction motor is reversed by reversing the phase sequence of the three voltages. One advantage of the vector-controlled drive is the ease of reversing speed with the same hardware configuration by reversing speed command signal which results in reversing torque producing component current and consequently speed direction of the motor. Fig. 9 shows the transient response of the drive when the command speed is changed suddenly. The speed is reversed through regenerative braking mode where the power is recovered back to the supply that means vector control is capable to drive IM in four-quadrant operations (Edward and Sen, 1988). Therefore, vector controlled induction motor drives can be used for high performance application such as servo drives and steel mill controls. Dynamic braking or regeneration can be implemented. When the torque command reference is simply reversed in polarity a torque will be produced in the opposite direction and mechanical energy not dissipated in the winding resistance is returned to the supply (Lin, Su and Yuan, 1997).

8. Field weakening operation

One advantage of using vector control of an induction machine is the capability of operation at speeds above the base speed in the field-weakening region. This is possible by driving the machine at its maximum rated voltage, but with a frequency above the rated supply frequency. In vector control, there is achieved by controlling the frequency supplied to the machine; such that the speed is increased by reducing the flux producing command reference current. This results in a weaker field in the machine reducing the back EMF terms analogous to a separately excited DC machine. Below base speed, the machine operates at constant flux but above the base speed, the flux is weakened inversely proportional to the speed during which, the power available is constant, without exceeding the voltage rating of the machine. The disadvantage with field weakening is that the maximum level of torque available is reduced due to the lower rotor flux. With reference to fig. (1), the command current $i^{e}_{ds}{}^{*}$ is adjusted such that, when the command speed ω_r^* is below the base speed during constant torque region, the command stator current $i^{e}_{ds}{}^{*}$ is kept constant, whereas, when ω_r^* is above the base speed, the current $i^{e}_{ds}{}^{*}$ is automatically decreased such that the power is kept constant without exceeding the rated voltage. Fig. 10 shows the performances of the machine using vector controlled drive in field weakening region. At the time t_1 the command speed ω_r^* is increased from 93% to 105% of base speed and the command *d*-axis stator current $i^{e}_{ds}{}^{*}$ is reduced from 100% to 60% of rated value. Again, at time t_2 the command speed is increased from 105% to 110% of base speed and the command *d*-axis stator current $i^{e}_{ds}{}^{*}$ is reduced from 60% to 30% of rated value. By reducing the field command current to an appropriate level depending on the load torque, and increasing the torque command current to compensate for the reduced flux, more efficient operation of the induction machine is possible (Rajashekara, Karvamura and Matsuse, 1996). This is only possible where the load torque is small and significant power would otherwise be lost in maintaining the rated flux.

9. Comparison between IM and DC drive

Table (1) shows a comparison between vector controlled IM drive shown in fig. 1 and separately excited DC motor drive shown in fig. 4. It should be noted that the power rating of the application is an important factor to decide which drive is preferred. For low power rating applications, although the DC motor is more expensive than IM but the overall DC drive is less expensive than overall IM drive because the vector control should be implemented by a high speed signal processor but for high power rating applications, the IM drive is less expensive than DC motor drive as the machine cost dominates the cost of the whole drive (Wiley and Sen, 1997).

		IM drive	DC Drive
Cost	M/C	Less	More
	Power Electronics	More	Less
	Control Circuit	More	Less
	Measurements	More	Less
Maintenance		Less	More
Field Weakening		Available	Available
Speed reversal		Available	Available

Table (1). Comparison between IM drive and DC drive.

10. Conclusion

This paper has studied the indirect vector-controlled induction motor drive. The conventional speed control methods are reviewed and the fundamental concept of vector control and the dynamic model are presented. The steady state and transient analysis are illustrated where the effect of both torque and d-axis command current on performance is analyzed. The vector controlled induction motor behaves almost like a separately exited DC motor. It is shown that the *q*-axis synchronous stator current i^e_{qs} behaves in a similar manner as the armature current I_a and the *d*-axis synchronous stator current i^e_{ds} behaves in a similar manner as the field current I_f. Vector control of induction motor can change instantaneously magnitude and position of armature current. Reversing speed direction of IM can be achieved using the same hardware configuration. Also, the induction motor can run above base speed at the same rated voltage via field weakening operation mode. Each of DC motor and vector controlled induction motor has advantages and disadvantages. The choice between them depends on the nature of the application.

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دراسة تحليلية لإدارة محرك الحث المغناطيسي بالنظام المتجه

أدى التقدم في استخدام منظومات إلكترونيات القوى الصناعية في إدارة الالات الي امكانية تشغيل محرك الحث والتحكم في سرعته بطريقة مماثلة تماما لمحرك التيار المستمر. تقدم هذه الورقة البحثية دراسة تحليلية للتحكم المتجهي لمحرك الحث المغناطيسي باستخدام طريقة مباشرة , تم شرح المبادئ النظرية الأساسية التي توضح فكرة التحكم المتجهي لمحرك الحث وكذلك استنتاج نموذج تحليلي. تم دراسة تأثير كلا من المركبة العزمية والمركبة الفيضية لتيار عضو الاستنتاج علي الاستجابة النهائية للمحرك وكذلك تم الاستنتاج على الاستجابة النهائية للمحرك وكذلك تم استنتاج الاستجابة الانتقالية لمحرك الحث وعمل مقارنة بينه وبين محرك التيار المستمر لبيان صحة ادعاء تشغيل محرك الحث بطريقة مماثلة لمحرك التيار المستمر وكذلك عقد جدول مقارنة بين إدارة المحرك لبيان العوامل المختلفة التى قد تؤثر في اختيار أحدهما

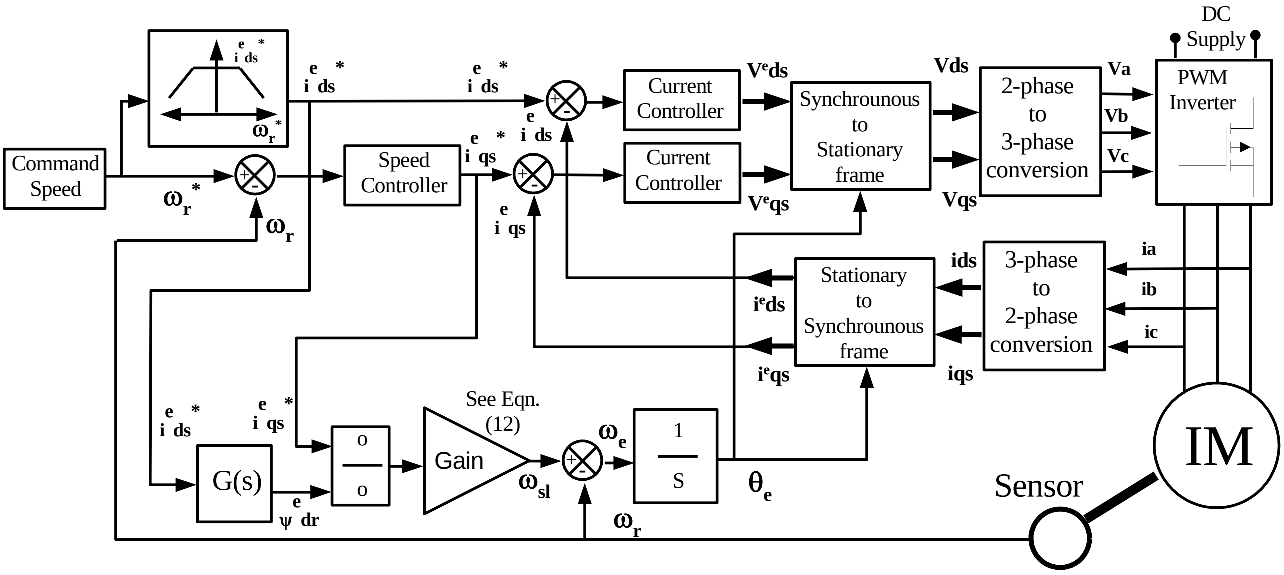


Fig. 1 Block diagram of the indirect field oriented control.

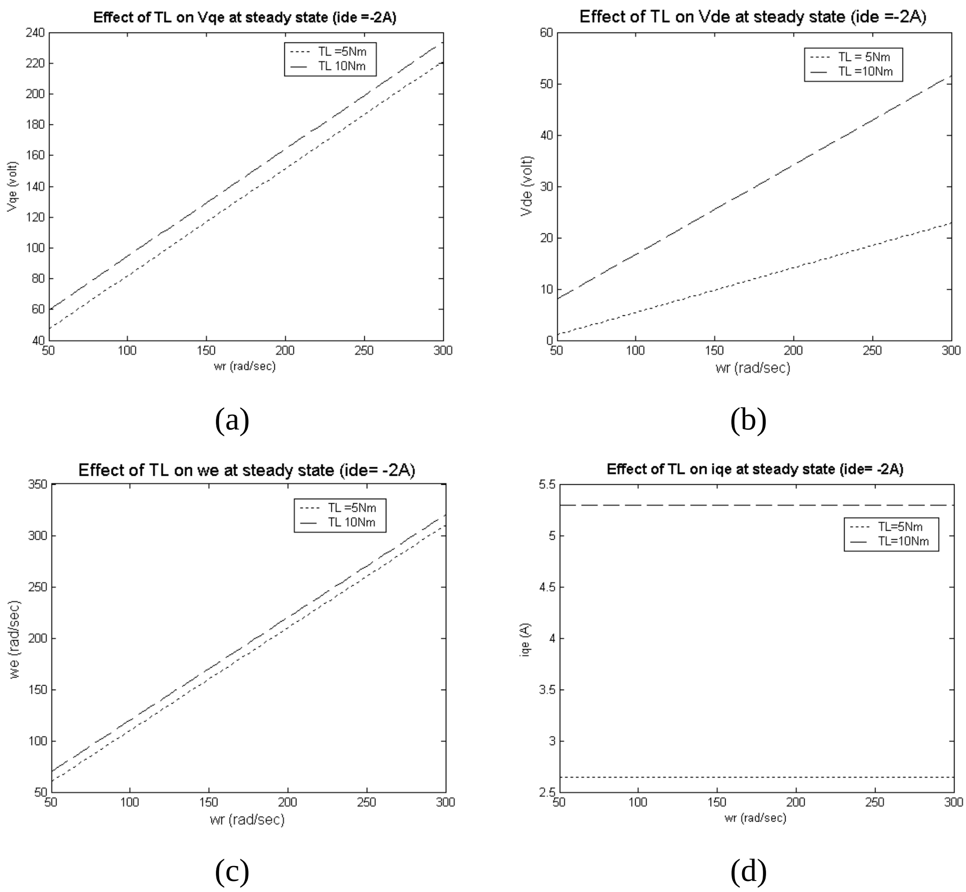


Fig. 2 Relationship between ω_r and: (a) v^e_{qs}, (b)v^e_{ds}, (c) ω_e and (d) i^e_{qs}

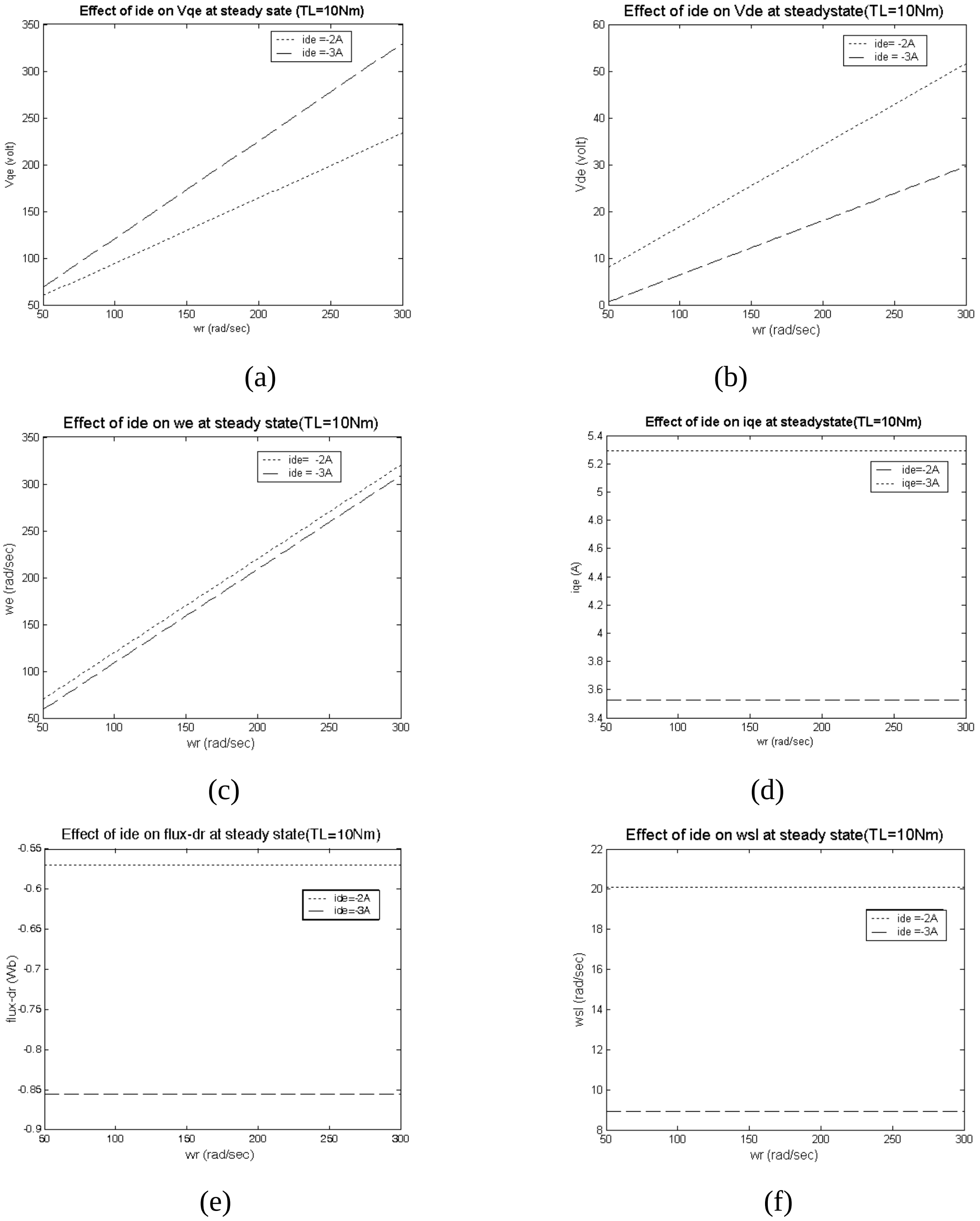


Fig. 3 Relationship between ω_r and: (a) v^e_{qs}, (b) v_{ds}, (c) ω_e, (d) i^e_{qs}, (e) ψ^e_{dr}, (f) ω_{sl}

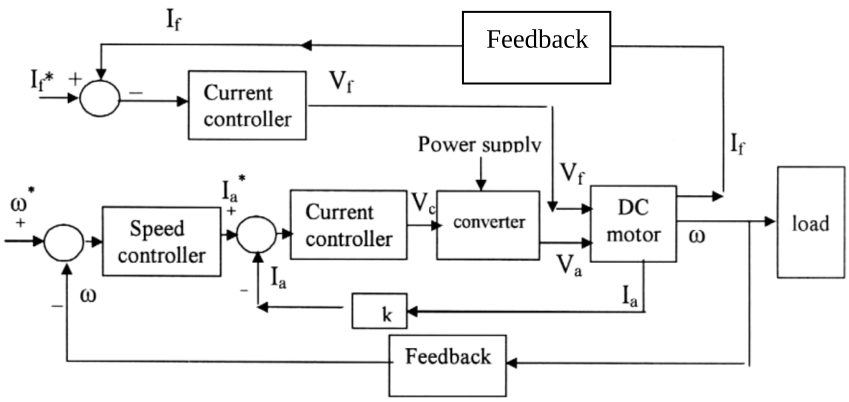
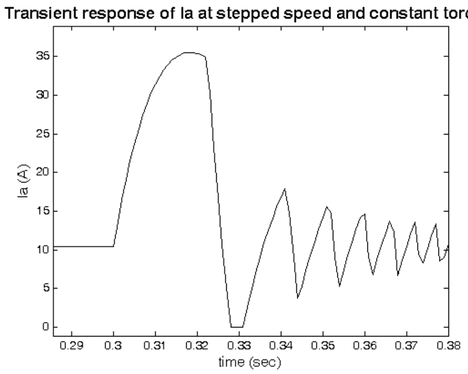
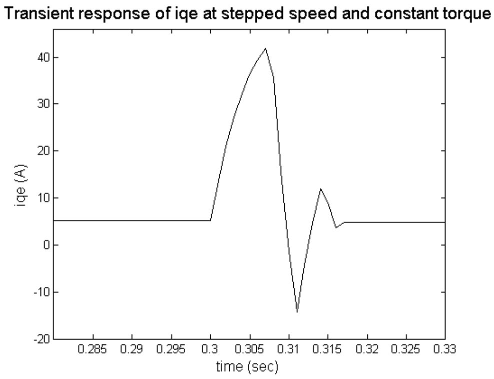


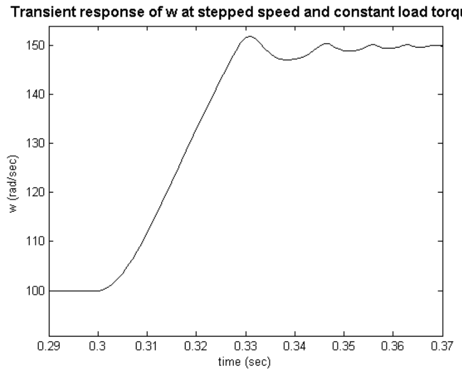
Fig. 4 Closed loop speed control of DC motor with inner current loop.



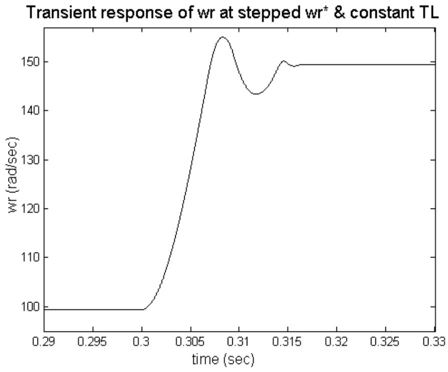
(a)



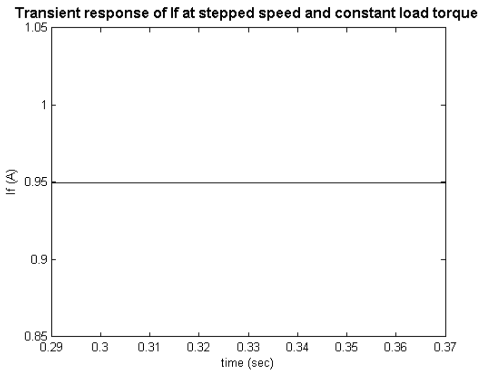
(b)



(c)



(d)



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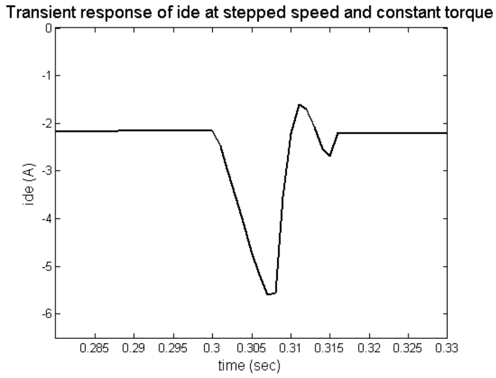
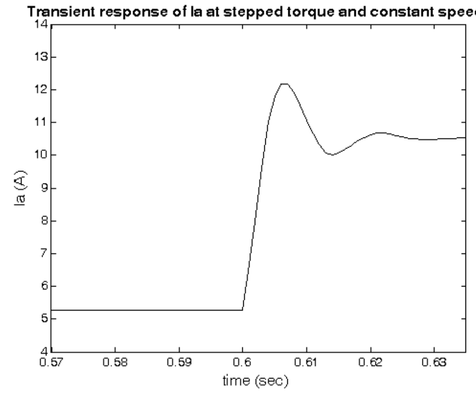
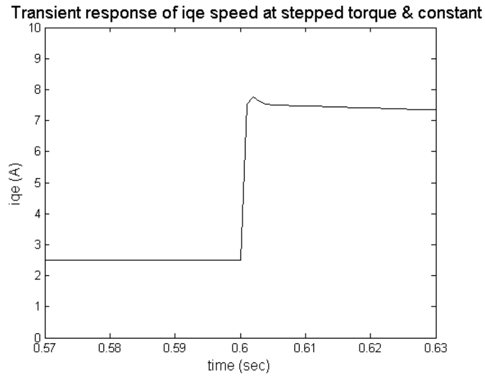


(f)

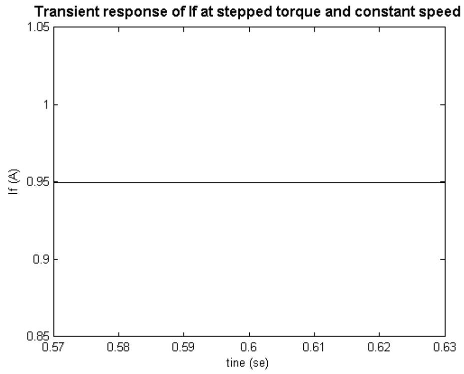
Fig. 5 Relationship between time and: (a) armature I_a, (b) q-axis synchronous current i^e_{qs}, (c) DC motor speed ω, (d) induction motor speed ω_r, (e) field current I_f, (f) *d*-axis synchronous current i^e_{ds}, for step change in speed and constant load torque.



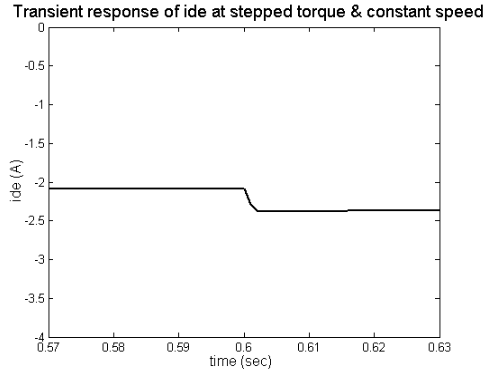
(a)



(b)

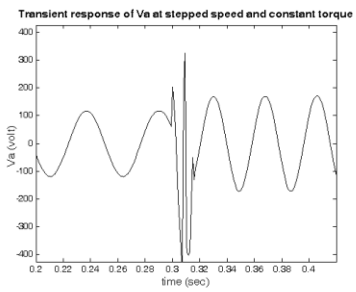


(c)

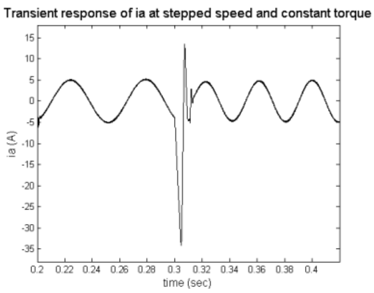


(d)

Fig. 6 Relationship between time and: (a) armature current I_a , (b) *q*-axis synchronous current i^e_{qs}, (c) field current I_f , (d) *d*-axis synchronous current i^e_{ds}, for step change in load torque.

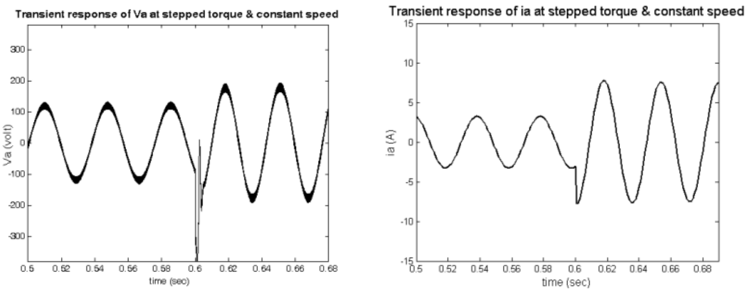


(a)



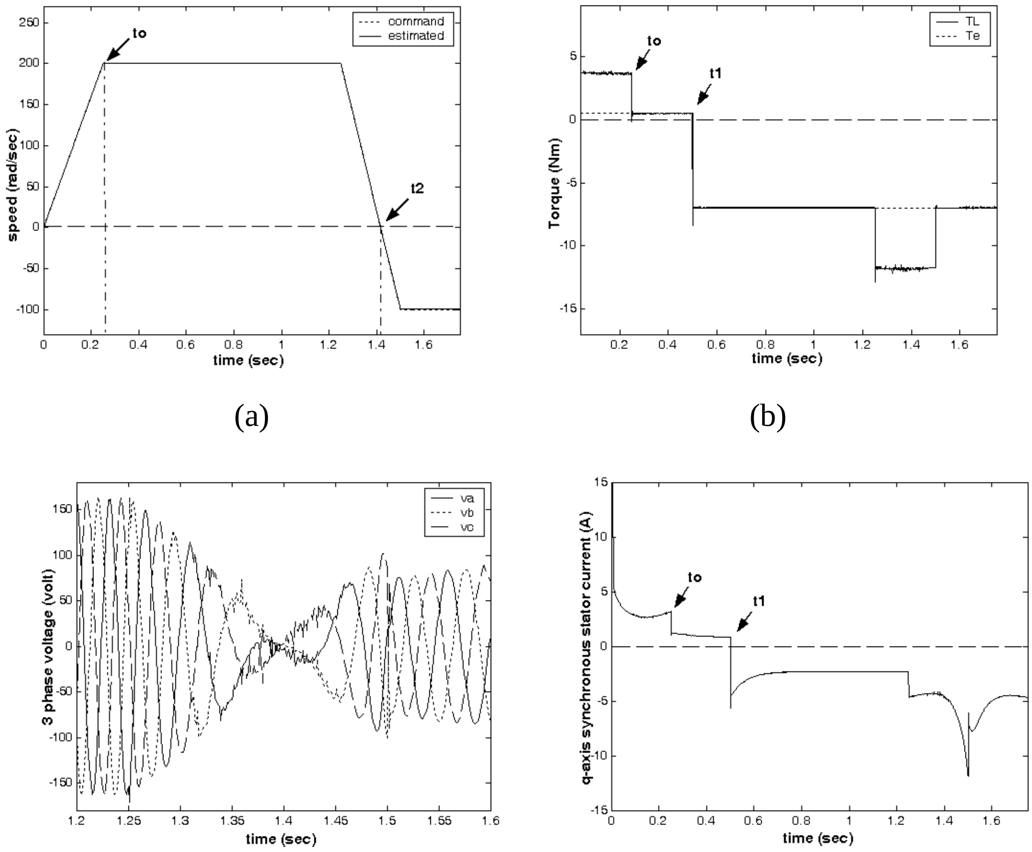
(b)

Fig. 7 Relationship between time and: (a) the phase-a voltage Va, (j) The phase-a current Ia



(a) (b)

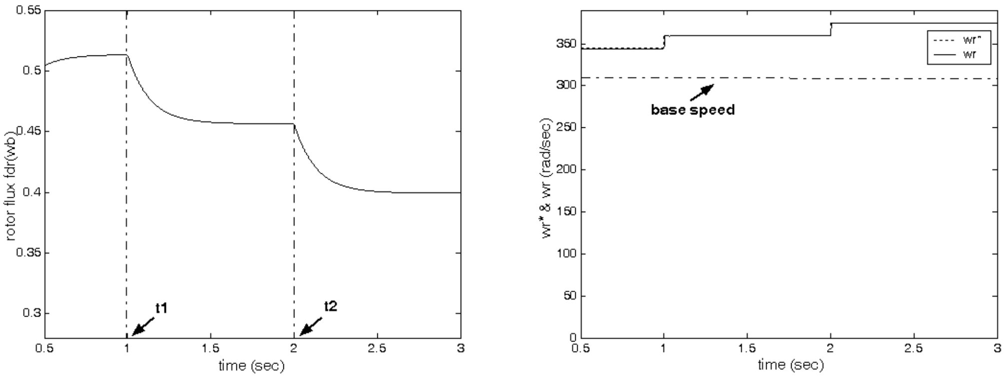
Fig. 8 Relationship between time and: (a) the phase-a-current I_a, (g) The phase-a-voltage V_a,



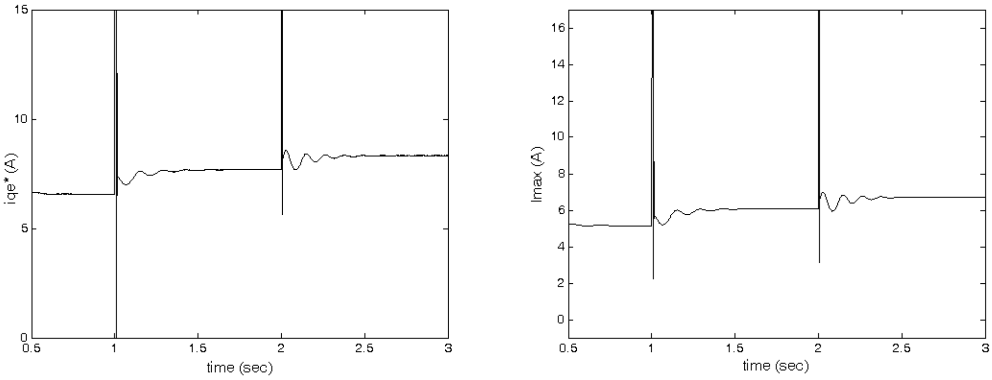
(a) (b)

(c) (d)

Fig. 9 Relation of time and (a) output speed, (b) torque, (c) three phase voltages, (d) synchronous stator current.



(a) (b)



(c) (d)

Fig. 10 Relationship between time and:(a) ω_r, (b) ψ_r, (c) i_{qe}^* and(d) $i_{a\text{-}max}$