Vector control of repulsion motor

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This paper describes an attempt for controlling the speed and torque of the repulsion motor (RM) drive using the vector control technique. The RM has been modeled in an arbitrarily rotating synchronous reference frame, where the torque and flux can be decoubled and controlled. All the stator-referred quantities are resolved into forward and backward rotating components before transforming them to the synchronous frame. The direct axis of this frame is chosen to be aligned with the forward component of the rotor current vector. The field orientation conditions can be established by selecting the steady state forward model of the RM in the synchronous frame as the reference model. Digital simulations have been carried out in order to validate the proposed vector control scheme. The MATLAB / SIMULINK software package has been employed to simulate such scheme. Simulation results show that good performance can be achieved whatever changes occur in speed and torque conditions.

يمتلك المحرك التنافرى ميزة هامة فى مواجهة المحركات الاخرى ذات الوجه الواحد وهى أنه يعطى اكبر عزم دوران لكل امبير عند بدء الحركة . وبالرغم من ذلك فان مجالات استخدام ذلك المحرك تكاد تكون شبه معدومة وذلك لأنه بالاضافة الى احتوائه على عضو التوحيد بمشاكله المعروفة فان له عيبا رئيسيا وهو هبوط سرعته هبوطا شديدا بمجرد تحميله ، وهو ما جعل المحرك الحثى يتفوق عليه . ويقدم هذا البحث امكانية استخدام طريقة التحكم الموجه للتحكم فى سرعة وعزم المحرك التنافرى. ولهذا الغرض تم تقديم معادلات هذا المحرك فى المستوى الزمنى الثابت ، واستخدام نظرية المجال المزدوج الدائر فى تحليل جميع المتغيرات الى مركبتين احداهما أمامية والاخرى خلفية . وقد تم عمل نموزج للمحرك التنافرى فى مستوى اختيارى يدور بسرعة التزامن وتحويل جميع المتغيرات اليه . وقد اختير المستوى الجديد بحيث ينطبق أحد محاوره على المركبة الأمامية لتيار عضو الاستنتاج . وقد تم عمل تحليل رياضى لمعادلات المحرك التنافرى فى المستوى الجديد واشتقاق الشروط اللازمة لتحقيق التحكم الموجه فيه .هذا وقد تم تمثيل النظام المقترح على الحاسب الالى وأظهرت النتائج نجاح طريقة التحكم الموجه مع المحرك التنافرى مهما تغيرت ظروف التشغيل .

Keywords: Repulsion motor, Vector control.

1. Introduction

The RM is an ac commutator machine having a single phase distributed winding (field) on the stator and a standard dc winding on the rotor. The rotor (armature) is equipped with a commutator and a pair of short circuited brushes displaced from the neutral axis. The RM possesses two extremely desirable characteristics: high starting torque, and low starting current. Thus, the RM develops more starting torque per ampere than any other type of single phase motors. On contrast, the RM has poor speed regulation in the normal operating range and unfavorable commutation conditions.

The analysis and control of the RM have been attempted in few refs. [1-5]. All of these researches aimed to control the speed of the RM electronically using a triac in the stator or in the rotor circuits. In recent years, vector control is the most significant development in the area of adjustable speed ac motor drives. Thus, it is possible to control an ac motor in a manner similar to the control of a separately excited dc motor and achieve the same quality of dynamic performance [6]. The high quality of dynamic performance of the separately excited dc motor is a consequence of the fact that its armature and field circuits are magnetically decoupled.

In this paper, the vector control technique has been employed in the RM in order to achieve good dynamic performance. Thus, the vector controlled RM will be suitable for driving high starting loads such as washing machines, lifts, locomotives, industrial processes,...etc. The RM has been analyzed using the double revolving field theory [7] together with the state space vector theory [8].

The flux and torque components of the stator current are separated and controlled in an arbitrarily selected synchronous frame. All the stator-referred quantities are resolved into forward and backward components before transforming it to the synchronous frame. The direct axis of the synchronous frame is chosen to be aligned with the forward rotor current vector. The field orientation conditions have been proved via considering the steady state forward model of the RM in the synchronous frame as the reference model. Computer Simulations have been carried out in order to verify the robustness of the proposed vector control scheme. The results prove that the vector control technique can be applied successfully to control the speed and torque of the repulsion motor drive.

2. Mathematical model of the RM

The RM consists of a dc armature rotating in an alternating magnetic field. The brush axis is displaced from the field axis by an electrical angle ϕ as shown in fig. 1. The dynamic model of the RM in the $\alpha-\beta$ stationary frame can be described as [9],

$$\begin{bmatrix} v_{\alpha s} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & L_m p & 0 \\ L_m p & R_r + L_r p & \omega_r L_r \\ -\omega_r L_m & -\omega_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\alpha r} \\ i_{\beta r} \end{bmatrix}, \quad (1)$$

where

$i_{\alpha s} = i_s$, $v_{\alpha s} = v_s$, $i_{\alpha r} = i_r \cos\phi$,

$i_{\beta r} = i_r \sin\phi$, and

i_s, v_s, i_r: are the space vectors of the stator current, stator voltage, and rotor current.

R_s, R_r: are the stator, and rotor resistance.

L_s, L_m, L_r: are the stator, magnetizing, and rotor inductance.

p is the differential operator, d/dt.

ω_r is the electrical angular rotor speed.

Eq. (1) can be written alternatively in terms of the α-β stator and rotor flux linkages,

$$\left.\begin{aligned} v_{\alpha s} &= R_s i_{\alpha s} + p\lambda_{\alpha s} \\ 0 &= R_r i_{\alpha r} + p\lambda_{\alpha r} + \omega_r \lambda_{\beta r} \\ 0 &= R_r i_{\beta r} + p\lambda_{\beta r} - \omega_r \lambda_{\alpha r}. \end{aligned}\right\} \quad (2)$$

Where

$$\lambda_{\alpha s} = L_s i_{\alpha s} + L_m i_{\alpha r},$$
$$\lambda_{\alpha r} = L_r i_{\alpha r} + L_m i_{\alpha s},$$
$$\lambda_{\beta r} = L_r i_{\beta r}.$$

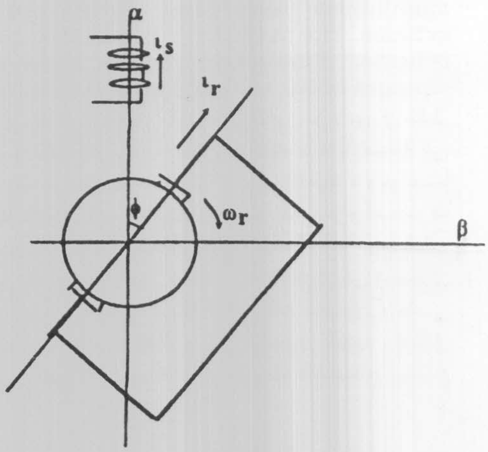

Fig. 1. Schematic diagram of the repulsion motor.

The mechanical motion of the RM can be described as,

$$P.(T_e - T_L) = (Jp + f).\omega_r, \quad (3)$$

where P is the number of pole pairs, T_e is the electromagnetic torque developed by the motor, T_L is the load torque, J is the moment of inertia and f is the friction coefficient.

The electromagnetic torque developed by the RM is then given by,

$$\begin{aligned} T_e &= -P.L_m.i_{\beta r}.i_{\alpha s} \\ &= -P.\frac{L_m}{L_r}.\lambda_{\beta r}.i_{\alpha s}. \end{aligned} \quad (4)$$

3. Torque control requirements

The objective in vector control is to separate out the stator current into two components; one for creating the flux and the other for creating the torque. These components are controlled independently in a de-coupled manner as in a separately excited dc motor. The analogy of the RM system to a dc machine is apparent in the sense of producing a fixed space angle between the field flux and armature MMF regardless of the rotor speed. Unlike the dc motor, the field flux and armature MMF in the RM are not in space quadrature. As a consequence, a magnetic coupling exists between the field and armature circuits. Therefore, the requirements for torque control of the RM are :

i) Independent control of the flux and torque components of the stator current.
ii) Independent control of the spatial angle between the rotor flux and the torque component of the stator current such that they are orthogonal.

If these requirements are met at every instant of time, an instantaneous torque control would result. This can be accomplished by transforming the machine model expressed by eqs. (2, 3) to an arbiterarily selected rotating reference frame. In a 3-phase balanced machine system, the synchronous frame is especially interesting since here the stator space vectors (such as voltage, current and flux) are stationary and have constant dc values.' In a single-phase machine system like the RM, the single phase pulsating quantities are firstly resolved into two rotating components (forward and backward) before transforming it to the synchronous frame. In this case, the forward component becomes dc while the backward component pulsates at twice supply frequency. This is to be explained in the next section values. In a single phase machine system like the RM, the single phase pulsating quantities are firstly resolved into two rotating components (forward and backward) before transforming it to the synchronous frame. In this case, the forward component becomes dc while the backward component pulsates at twice supply frequency. This is to be explained in the next section.

4. Analysis of the RM in the synchronous frame

The RM is a singly fed machine, receiving electrical input from the stator side only. When the stator winding is connected to a single-phase supply, then it produces a sinusoidally space distributed MMF whose peak value pulsates with time. The space vector of the stator current can be defined as

$$i_s = I_s \cos\theta_s ,$$

where I_s is the magnitude of the stator current space vector, and θ_s is the spatial angle measured from the stator (field) axis which can be expressed as the integral of the stator current angular frequency

$$\theta_s = \int \omega_s . dt .$$

As the magnetic axis of the rotor is displaced by an angle ϕ from the field axis, then the rotor current space vector can be represented by:

$$i_r = I_r . \cos(\theta_s + \phi) ,$$

where I_r is the magnitude of the rotor current space vector. Using the double revolving field theory, each of the pulsating stator and rotor current space vectors can be resolved into two vectors having equal magnitudes and rotating with angular speed ω_s in opposite directions (forward and backward) as seen in fig. 2.

$$i_s = \frac{I_s}{2}[e^{j\theta_s} + e^{-j\theta_s}] = i_s^f + i_s^b , \tag{5}$$

$$i_r = \frac{I_r}{2}[e^{j\theta_s} + e^{-j\theta_s}].e^{j\phi} = i_r^f + i_r^b , \tag{6}$$

where:

i_s^f, i_s^b are the forward and backward components of the stator current space vector, and

i_r^f, i_r^b are the forward and backward components of the rotor current space vector.

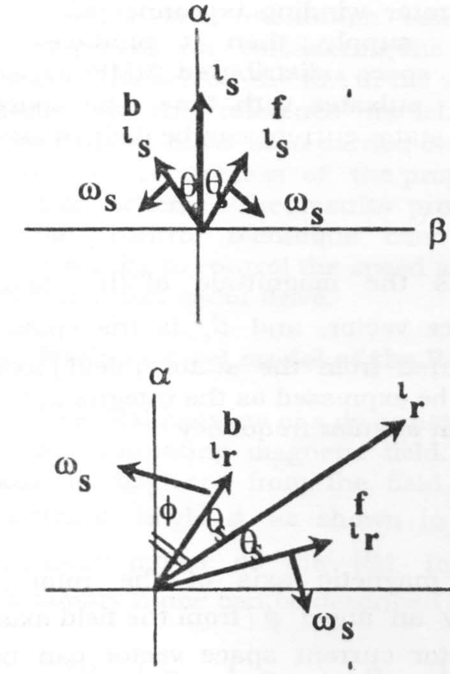

Fig. 2. Resolving the stator and rotor current space vectors into two equal opposite rotating vectors.

For decoupling control of the RM to be achieved, all the stator referred variables are projected on a d-q synchronous frame rotating with angular speed ω_s. The new frame is selected such that its d-axis is aligned with the forward component of the rotor current space vector. In this case, the d-q stator current space vector would become (with the aid of eq. (5)).

$$i_{dqs} = i_s.e^{-j(\theta_s+\phi)} = \frac{I_s}{2}.e^{-j\phi}(1+e^{-j2\theta_s}) = i^f_{dqs} + i^b_{dqs}, \quad (7)$$

where i^f_{dqs}, i^b_{dqs} are the forward and backward components of the stator current space vector in the d-q synchronous frame.

The individual components of the d-q stator currents can be written using eq. (7) as:

$$\left.\begin{aligned} i^f_{ds} &= \frac{I_s}{2}\cos\phi \ldots,\ldots i^b_{ds} = \frac{I_s}{2}\cos(2\theta_s+\phi) \\ i^f_{qs} &= -\frac{I_s}{2}\sin\phi,\ldots i^b_{qs} = -\frac{I_s}{2}\sin(2\theta_s+\phi) \end{aligned}\right\}. \quad (8)$$

Similar expressions can be obtained for the d-q stator voltage.

The rotor current in the d-q synchronous frame can be described using eq. (6) as:

$$i_{dqr} = i_r.e^{-j(\theta_s+\phi)} = \frac{I_r}{2}[1+e^{-j2\theta_s}] = i^f_{dqr} + i^b_{dqr}, \quad (9)$$

where i^f_{dqr}, i^b_{dqr} are the forward and backward components of the rotor current space vector in the d-q synchronous frame.

The d-q components of the rotor current are expressed with the aid of eq. (9),

$$\begin{aligned} i^f_{dr} &= \frac{I_r}{2} \ldots,\ldots\ldots i^b_{dr} = \frac{I_r}{2}.\cos 2\theta_s \\ i^f_{qr} &= 0\ldots\ldots,\ldots\ldots i^b_{qr} = -\frac{I_r}{2}\sin 2\theta_s \end{aligned} \quad (10)$$

The rotor flux linkage can be described in the d-q synchronous frame as:

$$\lambda_{dqr} = L_r i_{dqr} + L_m i_{dqs}.$$

Using eqs. (7) and (9), the value of the rotor flux linkage would become,

$$\lambda_{dqr} = \frac{1}{2}(L_r I_r + L_m I_s e^{-j\phi})(1+e^{-j2\theta_s}) = \lambda^f_{dqr} + \lambda^b_{dqr}, \quad (11)$$

where λ^f_{dqr}, λ^b_{dqr} are the d-q forward and backward components of the rotor flux linkage which can be separated into its individual d- and q- components,

$$\begin{aligned} \lambda^f_{dr} &= \frac{1}{2}(L_r I_r + L_m I_s \cos\phi), \\ \lambda^b_{dr} &= \frac{1}{2}[L_r I_r \cos 2\theta_s + L_m I_s \cos(2\theta_s+\phi)], \\ \lambda^f_{qr} &= -\frac{1}{2}L_m I_s \sin\phi, \\ \lambda^b_{qr} &= -\frac{1}{2}[L_r I_r \sin 2\theta_s + L_m I_s \sin(2\theta_s+\phi)]. \end{aligned} \quad (12)$$

Similar expressions for the d- and q- stator flux linkages can be obtained.

The electromagnetic torque of the RM can be expressed in the synchronous frame as

$$T_e = P\frac{L_m}{L_r}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}), \quad (13)$$

which yields after expansion (using eqs. (8) and (12)) two terms; an average torque and a pulsating torque at $2\omega_s$; i.e.

$$T_e = -P.L_m \frac{I_s I_r}{2} \sin\phi(1+\cos 2\theta_s) \ . \quad (14)$$

The preceding discussions reveals that all the d-q stator referred variables consist of an average dc forward component superimposed upon a sinusoidal ac backward component pulsating at twice the stator frequency.

5. Vector control strategy of the RM

The d-q model of the RM can be established simply by converting the stationary model expressed by eq. (2) to an arbitrarily rotating synchronous frame. Since these equations are linear, the forward and backward components are handled separately. Therefore, the forward d-q model of the RM can be expressed by the following equations

$$\begin{aligned} v^f_{ds} &= R_s i^f_{ds} + p\lambda^f_{ds} - \omega_s \lambda^f_{qs}, \\ v^f_{qs} &= R_s i^f_{qs} + p\lambda^f_{qs} + \omega_s \lambda^f_{ds}, \\ 0 &= R_r i^f_{dr} + p\lambda^f_{dr} - \omega_{sl}\lambda^f_{qr}, \text{and} \\ 0 &= R_r i^f_{qr} + p\lambda^f_{qr} + \omega_{sl}\lambda^f_{dr}, \end{aligned} \quad (15)$$

where ω_{sl} is the difference between the synchronous and actual motor speeds.

Similar equations can be obtained for the backward d-q model with ω_s replaced by $-\omega_s$. Since the forward variables appear as constant dc quantities in the synchronous frame, the steady state model can be obtained by eliminating the time derivative terms from eq. (15). Writing only the forward rotor circuit equations in the steady state:

$$\begin{aligned} 0 &= R_r i^f_{dr} - \omega_{sl}\lambda^f_{qr} \\ 0 &= R_r i^f_{qr} + \omega_{sl}\lambda^f_{dr} \end{aligned} , \quad (16)$$

where

$$\begin{aligned} \lambda^f_{dr} &= L_r i^f_{dr} + L_m i^f_{ds} \\ \lambda^f_{qr} &= L_r i^f_{qr} + L_m i^f_{qs} \end{aligned} . \quad (17)$$

As the forward rotor current is chosen to be aligned with the d-axis, therefore it has no component in the q-axis ,

$$i^f_{qr} = 0 \ . \quad (18)$$

It follows from eq. (16) that,

$$\lambda^f_{dr} = 0 \ . \quad (19)$$

Thus, the forward rotor flux is completely oriented in the q-axis. Using eqs. (18), (19), and substituting in eq. (17), it can be easily concluded that :

$$i^f_{dr} = -\frac{L_m}{L_r} i^f_{ds}, \quad (20)$$

$$\lambda^f_{qr} = L_m i^f_{qs} \ . \quad (21)$$

Eq. (21) describes that the q-axis forward stator current is responsible for producing the forward rotor flux. Of course, the orthogonal component i^f_{ds} is responsible for producing the forward torque. Combining eqs. (16,20,21), the slip frequency is found to be;

$$\omega_{sl} = -\frac{1}{T_r} \cdot \frac{i^f_{ds}}{i^f_{qs}}, \quad (22)$$

where T_r is the rotor time constant, $T_r = L_r / R_r$

Substituting from eq. (8) in (22), yields,

$$\omega_{sl} = \frac{1}{T_r \tan\phi} \ . \quad (23)$$

Eq. 23 indicates that if the brush axis is kept fixed at a certain angle ϕ, the slip frequency will be constant and independent of load and motor speed. This is attributed to the fact that the magnetic axis of the rotor is fixed in space with respect to that of the stator.

Using eq. (23), the stator frequency necessary for satisfying the field orientation will be

$$\omega_s = \omega_r + \frac{1}{T_r \tan\phi} \tag{24}$$

Eq. (24) reveals that at a certain brush angle ϕ, the stator frequency of a field oriented RM must be set in accordance with the motor speed. Thus, the stator frequency must be kept above the rotor frequency by a difference depending upon the initial set of the brush angle ϕ. On the other hand, If the brush axis is displaced by a negative angle ϕ, then the slip frequency will be negative. In this case, the stator frequency must be adjusted below the rotor frequency by the slip value to ensure field orientation. This would give the flexibility to keep the stator frequency at a low level at high speeds. The average electromagnetic torque developed by the field oriented RM can be calculated using eqs. (13) and (21).

$$T_e = -P\frac{L_m}{L_r}\lambda^f_{qr} i^f_{ds} = -P\frac{L^2_m}{L_r} i^f_{qs} i^f_{ds} \tag{25}$$

The relation between i^f_{ds}, and i^f_{qs} can be written using eq. (8),

$$i^f_{qs} = -i^f_{ds} \cdot \tan\phi \tag{26}$$

Thus, the relation between torque and flux components of the stator current is controlled via the brush angle ϕ.

Combining eqs. (25) and (26), the average torque can be written in terms of the torque producing forward current,

$$T_e = P\frac{L^2_m}{L_r}(i^f_{ds})^2 \tan\phi \tag{27}$$

Eq. (27) clearly shows that adjusting the torque current command only can control the average torque of the RM.

6. Control scheme

The block diagram of the proposed control scheme used for simulation is shown in fig. 3.

The actual speed ω_r is measured and compared with the reference speed ω^*_r. The speed error is fed to PI controller in order to generate the torque current command i^*_{ds}. Using eq. 26, the flux current command i^*_{qs} can be calculated. The d-q command currents are compared with the corresponding actual values, and the errors are fed to PI controllers to generate the reference voltages v^*_{ds} and v^*_{qs}. These voltages must be rotated through an angle $(\theta_s + \phi)$ in order to obtain the commanded stator voltage in the fixed frame which is applied on the RM through PWM inverter. The transformation from the stationary frame to the synchronous frame and vice versa can be obtained by summing the commanded slip frequency (calculated by eq. (23)) together with the rotor frequency and the resulted sum is integrated and then added to the brush angle.

The parameters of the vector control scheme are chosen as: sampling period = 0.1 ms, carrier frequency for the PWM =2.5 KHZ, gains of PI- controllers are Kp=Ki=0.1 for the speed loop, and Kp=0.05, Ki=300 for the d-q current loops.

7. Results

The proposed vector control scheme of the RM has been simulated on the digital computer using the Matlab/Simulink software package. The RM used in the simulation procedure has the following specifications [1]:
1/3 hp, 4-pole, 115 volt, 2.95 amp, 1430 rpm, simple repulsion motor.
Stator resistance = 8 ohm.
Stator self inductance = 2.2 ohm.
Rotor Resistance = 0.168 ohm.
Rotor self inductance = 0.033 henry.
Mutual inductance 0.076 henry.

Fig. 4-a shows the simulation waveforms of the proposed control scheme when the brush angle is assumed to be adjusted at 20°. The motor speed command is chosen such that it varies linearly during the starting period (1 sec.) and then a constant speed of 1000 rpm is kept during the remaining simulation time. The load torque is initially applied with a constant value equal to 0.5 p.u. from t=0 to t=3 sec., then a 0.5 p.u. step increase is assumed at t=3 sec.

It has been indicated in this figure that, the actual motor speed follows the command speed. A small dip is noted at the instant of applying the step disturbance in load torque, but the command level is restored fast.

It has been shown also that the average d-axis rotor flux is zero while the average q-axis flux depends on motor load. In other words, it can be said that the field orientation principle has been satisfied.

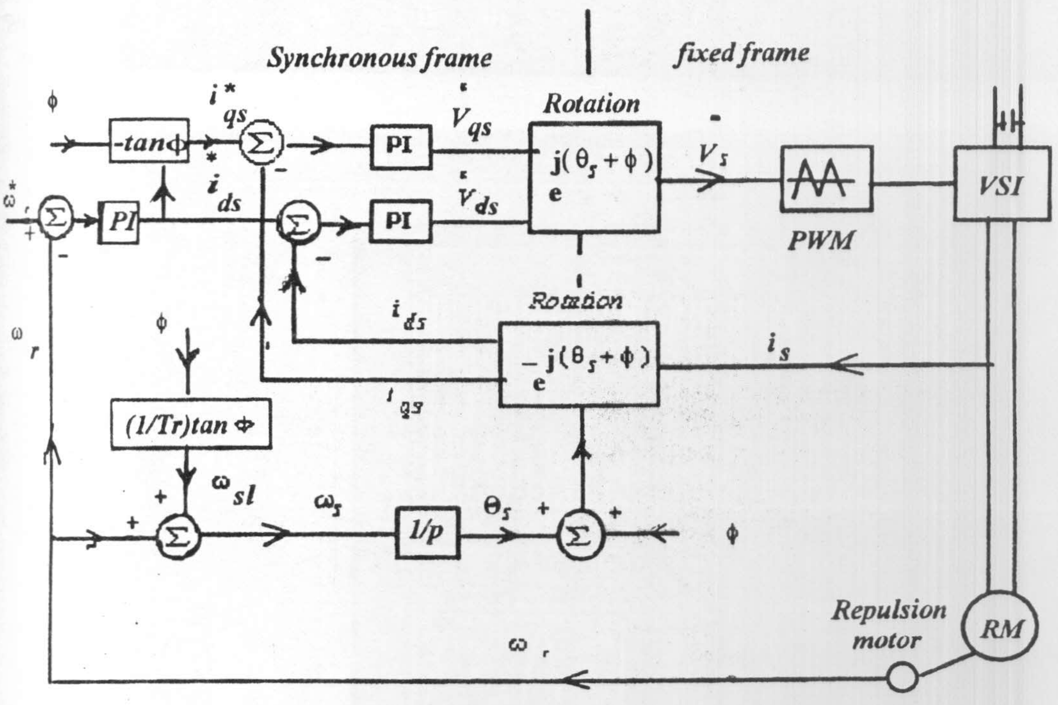

Fig. 3. Block diagram of the proposed control scheme.

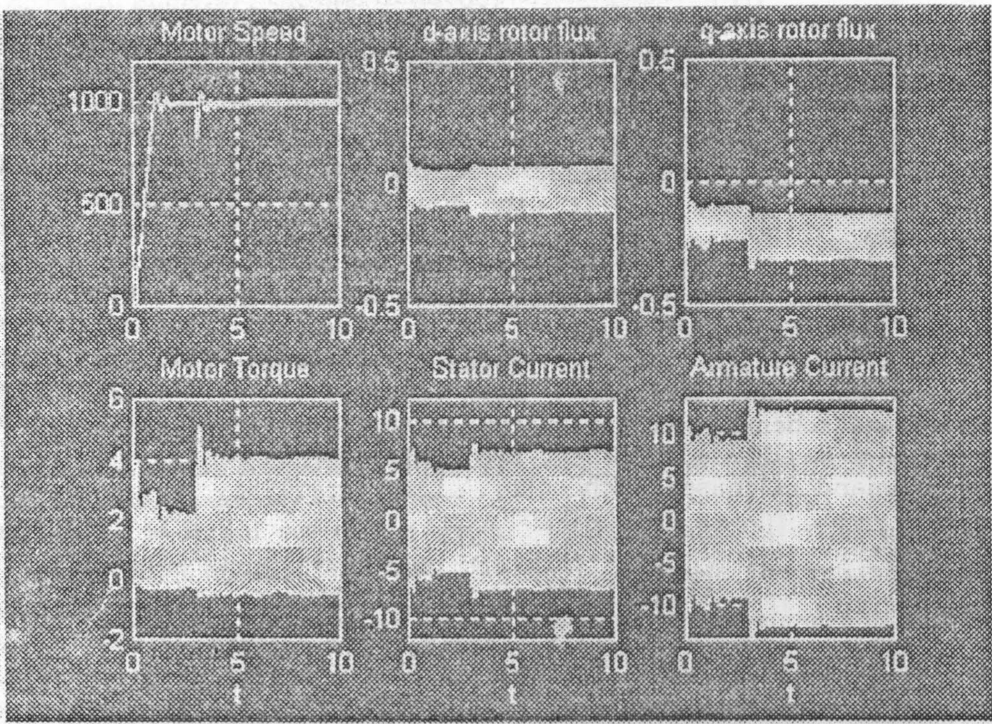

Fig. 4-a. Simulation waveforms of the proposed control scheme when the motor speed is kept constant and a step disturbance in load torque is applied at t = 3 sec.

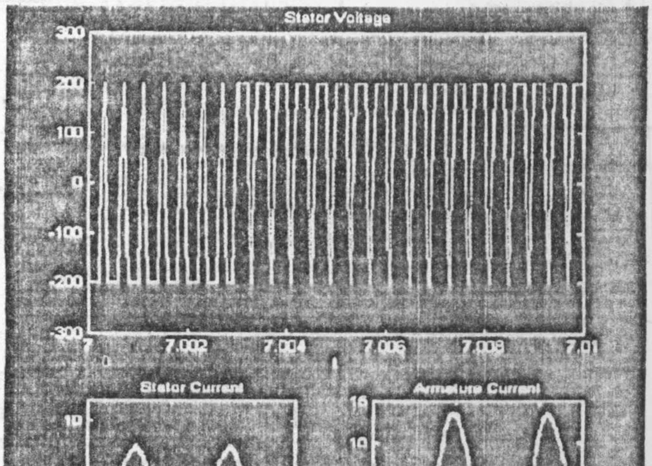

Fig. 4-b. Waveforms of the stator voltage, stator current and rotor current showing the inverter switching effects

The figure also records the fast response of motor torque, stator current and armature current to the change in load torque.

Fig. 4-b indicates the inverter switching effects on the stator voltage (during 10 ms), stator current and rotor current waveforms (during 50 ms).

Fig. 5 shows the simulation waveforms of the proposed control scheme when a constant 0.5 p.u. load torque has been applied on the motor and the command speed is assumed to drop linearly from 1000 rpm at t=4 sec. to 100 rpm at t=5 sec. Again, the actual motor speed follows the variation of the command speed. Also, an approximately zero average d-axis rotor flux has been recorded.

The figure also illustrates a slight reduction in the motor torque during the low speed region. This is attributed to the reduction in the torque required from the motor to overcome the friction torque. Consequently, the d-axis command current responds to this slight variation. According to eq. 26, the q-axis command current responds also to this variation. Therefore, the q-axis rotor flux has been slightly reduced (eq. 21) in the low speed region. Similar reductions in the stator and armature currents are noticed also in fig. 5 for the same reason.

In summary, the vector control technique can be applied successfully to the RM. The motor torque and rotor flux are decoupled and controlled independently. Thus, high performance can be achieved with the vector controlled RM drive.

8. Commutation quality

In ac commutator machines and so RMs, the commutation takes place under more unfavorable conditions than in the dc machines. This is due to the transformer emf induced in the short circuit winding element, which makes the commutation worse in comparison to that of the dc machine. Moreover, the commutation problem would be more difficult when the RM is fed through PWM inverters (as in our case) with its inherent high frequency switching. This effect can be reduced by:

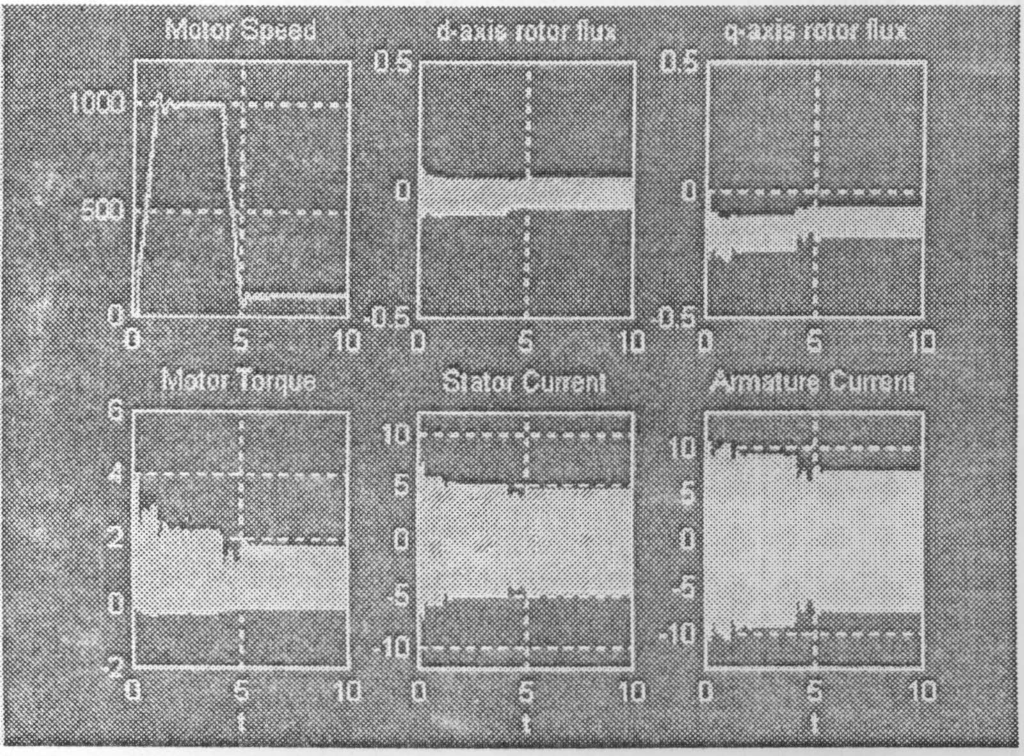

Fig. 5. Simulation waveforms when the load torque is kept constant at 0.5 p.u. and the motor speed is reduced from 1000 rpm at t=4s. to 100 rpm. at t=5 s.

1-Choosing the brush angle in such a way that the slip frequency command (eq. (23)) is as small as possible. Consequently, the RM will always operate near synchronous speed, at which the transformer emf becomes zero and therefore, the committing conditions become the most favorable.

2-Using a filter circuit on the output side of the inverter. Thus, the sinusoidal PWM inverters have the effect of shifting the harmonic frequencies to a high level, where they are more easily filtered.

9. Conclusions

This paper demonstrates that the vector control technique can be applied successfully for controlling the speed and torque of the RM. The field and armature circuits are magnetically decoupled in an arbiterarily synchronous frame. All the stator referred variables are resolved into forward and backward rotating components before they are converted into the synchronous frame. The direct axis of this frame is chosen to be aligned with the forward rotor current vector. The field orientation conditions are proved by considering the steady state forward model of the RM as the reference model.

Digital simulations have been carried out in order to validate the proposed control scheme of the RM drive. The results obtained show that the vector controlled RM drive has a high dynamic performance, and operates well whatever speed and torque conditions change.

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