Coupled Polyphase Reluctance Machines Without Rotating Windings

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Abstract

This paper discusses asynchronous electromechanical energy conversion of coupled polyphase reluctance machines without rotating windings. The scheme comprises two identical salient pole synchronous machines without rotating windings that are mechanically coupled together and electrically interconnected in parallel. The mechanism of torque production of the coupled set is uniquely presented in terms of the interaction between the stator mmf and the rotor permeance distribution.

List of Principal Symbols

B_1 - airgap flux density distribution in machine I
B_2 - airgap flux density distribution in machine II
e_{2f} - component of stator induced voltage at supply frequency (ω_o)
e_{2b} - component of stator induced voltage at slip frequency (ω_o-$2\omega_r$)
E_{1R} - induced voltage in the red phase of machine I
E_{2R} - induced voltage in the red phase of machine II
i_C - instantaneous circulating current
I_C - peak amplitude of the circulating current
i_f - instantaneous excitation current
I_F - peak amplitude of the instantaneous excitation current
k_1 - product of pitch and distribution factors
k - machine constant
m_1 - instantaneous mmf of machines I and II
M_o - peak amplitude of the instantaneous mmf
M_F - stationary field of the dc source
M_f - component of the stationary field and of equal amplitude as the peak of the rotating field.
M_x - component of the stationary field
M_1 - $Nk\omega_oI_f$
M_2 - $Nk(\omega_o-2\omega_r)I_C$
N - turns/pole/phase
P - number of pole pairs
P_o - the constant part of the rotor permeance distribution
P_1 - rotor permeance distribution of machine I
P_2 - rotor permeance distribution of machine II
P_v - the peak amplitude of the variable part of the rotor permeance distribution
t - time in seconds
ω_o - angular frequency of the excitation current
ω_r - angular speed of the rotor
Z_1 - impedance of machine I
Z_2 - impedance of machine II
β - phase angle of impedance
θ - angular distance round airgap

1.0 Introduction

The possibility that a motor can be operated asynchronously without rotor windings is not widely known; in spite of the fundamental pedagogic value of a principle which contradicts the elementary notions of how electromagnetic motion is produced in these machines.

Earlier studies on this class of machines had attempted to explain the mechanism of the torque production [1, 2]. Russell et al [1] explained the action in terms of the interaction of the harmonic components of the flux due to the stator mmf and the mmf induced in the primary by this flux. Broadway et al [2] explained the mechanism of torque production in terms of the interaction between the rotor primary flux and the flux induced in the stator winding by this flux itself. The machines discussed in [3, 4, 5] are single stack machines and belong to the same group of doubly excited machines. The only difference is that the main and the auxiliary windings have different number of magnetic poles, which respectively differ, from the number of magnetic poles of the rotor. Of the author mentioned above, it was only Ojo [5] who attempted to derive the torque equation in terms of d-q axes quantities. This approach, however, masks the actual mechanism of torque production.

In view of the fact that the rotor has neither rotating windings nor permanent magnet, the concept of torque in terms of the reluctance forces becomes an attractive one.

This paper is an attempt to explain the phenomenon of the torque production in terms of the total mmf distribution of the stator and the rotor permeance distribution by considering the machine strictly as a reluctance device. We consider this approach closer to the physical reality because since the rotor has neither rotating windings nor permanent magnet, the concept of a field originating from the rotor or being induced in the rotor can appear contrived.

2.0 Theory

Two identical reluctance machines without rotating windings are coupled together mechanically, and their stator windings connected in series phase by phase. Each machine has a second or auxiliary set of polyphase windings similar to the main windings. These are also connected in series phase by phase; in this case, however, the terminals of one of the machines are transposed. The axes of the rotors of the machine are in space quadrature.

Suppose the current in the main windings of the respective machines is dc, it will set up net stationary fields M_F and $-M_F$, which are in space opposition. The stationary fields and the rotating fields of machines I and II are shown in Figs 1(a) and (b) respectively.

Let the auxiliary windings be fed with polyphase current so that rotating fields represented by $M_f\exp(j\omega_r t)$ is produced in machines I and II respectively. These fields will also be related as shown in Fig. 1. The rotor will tend to lock in with the rotor pole axis aligned with the axis of the resultant field of the machine with the stronger net field; in this case, machine I.

The resultant field in machine I is given by:

$$M_{R1} = M_F + M_f\exp(j\omega_r t) \quad (1)$$

$$= (M_f + M_x) + M_f(\cos\omega_r t + j\sin\omega_r t) \quad (2)$$

$$= M_x + 2M_f\cos\tfrac{1}{2}\omega_r t \exp(j\,\tfrac{1}{2}\omega_r t) \quad (3)$$

where ω_r is the speed of the rotor relative to M_f. Similarly, the resultant field in machine II is given by:

$$M_{R2} = -M_F + M_f\exp(j\omega_r t) \quad (4)$$

$$= -(M_f + M_x) + M_f(\cos\omega_r t + j\sin\omega_r t) \quad (5)$$

$$= -M_x + j2M_f\sin\tfrac{1}{2}\omega_r t \exp(j\tfrac{1}{2}\omega_r t) \quad (6)$$

The rotor moving with angular speed $\frac{1}{2}\omega_r$ will lock in with the fields $-2M_f\cos\frac{1}{2}\omega_r t.\exp(j\frac{1}{2}\omega_r t)$ and $j2M_f\sin\frac{1}{2}\omega_r t \exp(j\frac{1}{2}\omega_r t)$. These fields like their rotors are in space quadrature and their resultant as viewed by an external observer looking longitudinally will appear as a single rotating field. Since the airgap permeance seen by the resultant field in either of the machines is the same, the resultant torque will be proportional to the sum of the squares of the mmf distributions. That is, the torque T α $\{\cos^2\frac{1}{2}(\omega_r t) + \sin^2\frac{1}{2}(\omega_r t)\}$. The sum of the squares is a constant and the torque is thus smooth and unidirectional but alternates between the machines. Fig. 2 illustrates the magnitude of the total effective torque mmfs as they rotate in the machine set. From Fig. 2, this net torque is given by $OC = \{(OB)^2 + (OB')^2\}^{1/2}$ and shown by the dotted circle. The preceding analysis assumes that M_x=0. The effect of a finite value of M_x is to introduce pulsation in the torque.

The same basic result can be obtained if the machines were connected in parallel as shown in Fig. 3, with direct current fed as indicated.

3.0 The coupled machines with the main and auxiliary windings excited by ac

The scheme comprises two identical polyphase salient-pole machines adapted from a laboratory teaching machine, Electric Machine Tutor (EMT) 180. These machines were modified from 4-poles to 2-poles and the salient pole rotors modified from 4-poles to 2-poles. Two such machines were mechanically coupled together such that when the d-axis of one rotor is aligned with the axis of a phase in one machine, the axis of the corresponding phase in the other machine is in alignment with the q-axis of its rotor, resulting in $\pi/2$ radians displacement between the d-axes of the machine elements. The electrical connection of the coupled machines as well as the orientation of the rotors are as shown in Fig. 4.

3.1 Analysis of the fields

The mmf of machine I is given by:

$m_1 = M_o\cos(\theta-\omega_o t)$..........................(7)

Since the rotor is of the salient pole type, the airgap permeance distribution may be expressed as:

$P_1 = P_o + P_v\cos2(\theta-\omega_r t)$......................(8)

Neglecting the third harmonic of flux, which can be eliminated by star connection, the airgap flux density distribution is expressed as:

$B_1 = m_1P_1 = M_oP_o\cos(\theta-\omega_o t)$

$+ \frac{1}{2}M_oP_v\cos(\theta+(\omega_o-2\omega_r)t)$...................(9)

The voltage E_{1R}, induced by B_1 in the red phase

$$E_{1R} = -2PNk_1\frac{d}{dt}\left(\int_{-\frac{\pi}{2p}}^{\frac{\pi}{2p}} B_1\, d\theta\right) \quad ......(10)$$

of the stator windings of machine I say, is obtained by evaluating the time variation of the total flux linkage. Thus:

$= e_{1f}\sin\omega_o t + e_{1b}\sin(\omega_o-2\omega_r)t$..............(11)

assuming a 2-pole machine.

For machine II, its primary mmf is the same as given by equation 7 but the axis of its rotor is $\pi/2$ radians displaced from that of machine I. Therefore, its permeance distribution is given by:

$P_2 = P_o + P_v\cos2(\theta-\omega_r t-\pi/2)$................(12)

$= P_o - P_v\cos2(\theta-\omega_r t)$......................(13)

Similarly, neglecting the third harmonics, the airgap flux density distribution of machine II is given by:

$B_2 = M_oP_o\cos(\theta-\omega_o t) - \frac{1}{2}M_oP_v\cos(\theta+(\omega_o-2\omega_r)t)$.......................................(14)

The voltage E_{2R} induced in the red phase of the stator winding of machine II by B_2 is given similarly by:

$E_{2R} = e_{2f}\sin\omega_o t - e_{2b}\sin(\omega_o-2\omega_r)t$...........(15)

The first terms of equations 11 and 15 are of mains frequency and are equal in magnitude and in time phase, but oppose the voltage supply. The second terms of equations 11 and 15 are in anti-phase and will thus aid the mains voltage in one machine and oppose it in the other respectively. The single phase equivalent circuit of the coupled machines showing the induced voltages is shown in Fig. 5 for the red phase only.

The emfs of e_{1b} and e_{2b} will add up in the local loop formed by the machine windings and produce a circulating current of the form:

$i_C = k(\omega_o-2\omega_r)I_c\cos((\theta-2\omega_r t) + \beta)$..........(16)

The excitation current is of the form:

$i_f = k\omega_oI_f\cos(\theta-\omega_o t)$..........................(17)

3.2 Torque of the machine

The overall current in each phase of the machine element is the combination of the mains current $2i_f$ which is shared equally by the machines and a circulating current i_C. The circulating current i_c while opposing the mains current in machine I will be aiding it in machine II. Consider machine I, the overall current in its winding is i_f-i_c and this will produce rotating mmf distribution in its airgap of the form:

$mmf_1 = Nk\omega_o I_f \cos(\theta-\omega_o t)$

$- \quad Nk(\omega_o-2\omega_r)I_c\cos(\theta+(\omega_o-2\omega_r t)+\beta$........(18)

$= M_1\cos(\theta-\omega_o t)-M_2\cos(\theta+(\omega_o-2\omega_r)t+\beta)$...(19)

The interaction of the two mmf components of equation 19 can be obtained by simple algebraic manipulation of subtracting and adding $M_2\cos(\theta-\omega_o t)$ to equation 19. Thus,

$mmf_1 = (M_1-M_2)\cos(\theta-\omega_o t) + 2M_2\cos(\theta-\omega_o t) -$

$M_2\cos(\theta+(\omega_o-2\omega_r)t+\beta)$..........(20)

Equation (20) could be re-written as :

$mmf_1 = (M_1-M_2)\cos(\theta-\omega_o t) -$

$2M_2\sin(\theta-\omega_r t+\beta/2)\cos((\omega_o-\omega_r)t+\beta/2)$. . . . (21)

It can be seen from equation (21) that $\sin((\theta-\omega_r t)+\beta/2)$ is an mmf wave which rotates in synchronism with the rotor but with a magnitude which pulsates according to $\cos((\omega_o-\omega_r)t+\beta/2)$. It will therefore impart a reluctance torque on the rotor, in a manner analogous to that of single phase reluctance machine. The wave $(M_1-M_2)\cos(\theta-\omega_o t)$ does not rotate in step with the rotor and will therefore not exert any torque on the rotor.

For machine II, the overall current in its winding is $i_f + i_c$. These currents will set up in its airgap an mmf of the form:

$mmf_2 = M_2\cos(\theta-\omega_o t)$

$+ M_2\cos(\theta+(\omega_o-2\omega_r)t+\beta)$..........(22)

Equation (22) can be re-written in an analogous manner to equation (21) as:

$mmf_2 = (M_1-M_2)\cos(\theta-\omega_o t)$

$+ 2M_2\cos(\theta-\omega_r t+\beta/2)\cos((\omega_o-\omega_r)t+\beta/2)$...(23)

Again, $\cos((\theta-\omega_r t)+\beta/2)$ is a wave which rotates in synchronism with the rotor and has a magnitude which pulsates according to $\cos((\omega_o-\omega_r)t+\beta/2)$. It will impart a reluctance torque on the rotor, in a manner analogous to that of single phase reluctance machine as well.

A comparison of equations 21 and 23 shows that the amplitude of torque producing mmf components in the respective machines are in time quadrature. When the mmf is maximum in one machine say, it will be minimum in the other machine.

The torque of the machine set will be directly proportional to the sum of the squares of the torque producing mmf waves. Since the torque producing mmf waves are in time quadrature, the sum of their squares is unity. This explains why the torque of the coupled machine set would be constant even though the torque of the coupled machine alternates form one machine to the other. The shifting of the torques from one machine element to the other is illustrated in Fig. 6.

This approach used above can be applied to explain the concept of torque mechanism in single stack machines. It can be shown that for a single stack machine with 2-pole and 6-pole stator windings and a 4-pole rotor say, the total mmf in the machine is given by [6].

$$mmf = (M_1 - M_2)\cos\left(\theta - \omega_0 t + \beta - \frac{\pi}{2}\right) + 2M_2\cos 2\left(\theta - \omega t - \frac{\pi}{4} + \frac{B_1 - B_2}{4}\right)\cos\left(\theta + (\omega_0 - 2\omega)t - \frac{B_1 - B_2}{4}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(24)$$

The first component of equation (24) does not move in synchronism with the rotor and therefore does not contribute to the torque of the machine. The first part of the second component is a wave, which rotates in synchronism with the rotor and thus will impart a reluctance torque to the rotor. This torque is however, modulated by the envelope of the 2-pole field of $\cos\left(\theta + (\omega_0 - 2\omega)t - \frac{B_1 - B_2}{4}\right)$ which rotates in the opposite direction to the rotor. Consequently, there will be ripple torque produced by this envelope, which explains the vibration and noise that are usually associated with this class of machines.

Conclusions and comments

Electromechanical energy conversion of coupled polyphase reluctance machines without rotor winding is presented. Although the device is a singly excited electromechanical device, the unique alignment of the rotors comprising the coupled set makes possible the existence of a circulating current in the machine windings in addition to the excitation current. The interaction of the mmf distributions of these currents in the respective machine comprising the coupled set produces a unidirectional torque, which swings cyclically from one machine element to the other such that the net torque of the coupled device remains constant. When the field of machine I say is being weakened, the field of machine II is being strengthened due to the flux of the circulating current which while adding to the mains flux in one machine will be subtracting from it in the other machine such that the net field remains constant. There is, therefore, a continuous shifting of the bulk of the load from one machine element to the other.

At synchronous speed, $\omega_r = \omega_o/2$, the magnitude of the circulating current drops to zero, and so there can be no synchronous torque at that speed. There will be torque, however, if dc current $i_{dc} = i_c$ (the circulating current) is injected into the system. Since the torque of the machine is directly proportional to the circulating current, any strategy, which enhances this current, will enhance torque. One method of enhancing this current is by reducing the reactance of the machine by the use of capacitors. This may be useful at a particular value of slip; in fact as the slip falls, the capacitor will act as large impedance and thus reduce torque. Alternatively, the current in the auxiliary winding can be boosted by injecting into it, current of suitable frequency and phase.

The device has a relatively low torque compared to an induction machine of the same size due to the inherent large leakage reactance, determined principally by the quadrature axis reactance of the winding [1].

Alternating current machines without rotating windings will have a future in a variety of special applications such as very low speed fixed frequency drives, linear motors for industrial transport systems, small brushless synchronous motors and generators.

References

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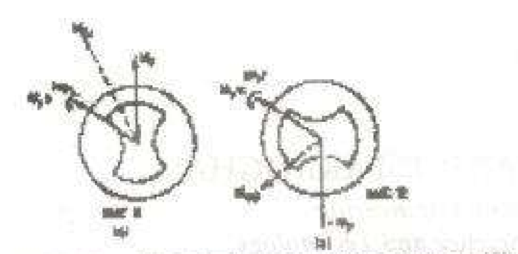

Fig 1: Illustration of the stationary and rotating fields in machines X and Y of the coupled set

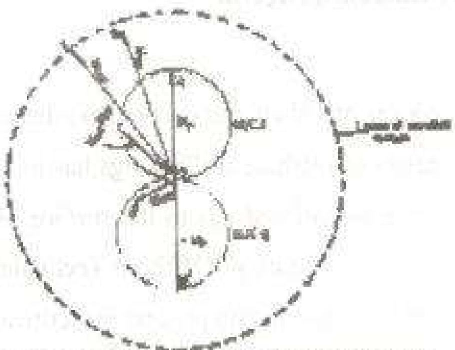

Fig 2: Illustration of the [illegible]

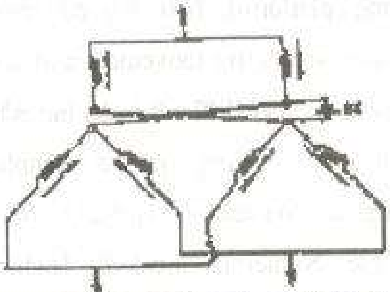

Fig 3: DC excitation of the coupled machines connected in parallel.

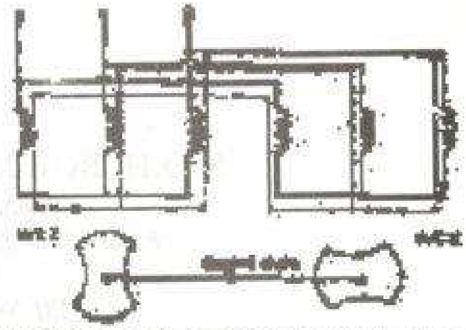

Fig 4: The electrical interconnection of the rotating windings and coupling of the shafts for the set.

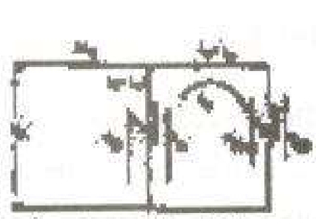

Fig 5: Single phase equivalent circuit of phase B showing the [illegible] voltages.

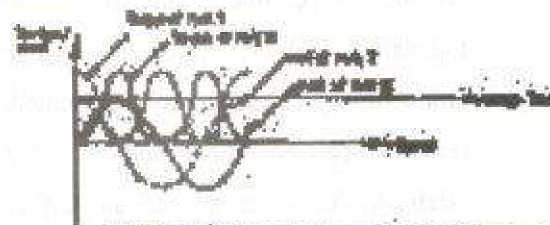

Fig 6: [illegible]