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A MAGNETIC RELIEF SCHEME FOR FOUR POLE INDUCTION MOTORS

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Abstract: It is well known that in radial air gap machines, two flux waves can produce an unbalanced magnetic pull if the two waves differ by two poles around the entire rotor periphery. The foregoing phenomena is employed in this paper in generating a net vertical force on the rotor of a four pole induction machine with the purpose of decreasing the net weight on the bearings. The decreased stress on the roller bearings should result in prolonging their life span. A drive is proposed in which a conventional four pole winding is utilized to obtain the effect of equivalent four pole and two pole windings simultaneously. In this case, the machine stator needs to have six independent windings with six terminals. The relationship between the radial force command and the required reference currents is derived for both no-load and loaded conditions. The proposed drive performance with current regulated PWM is examined via time domain simulations.

I. INTRODUCTION

Electric drive systems where the electric supply to the motor is utilized to provide both the torque output and an electromagnetic force for rotor levitation, have been recently proposed [1-7]. Such electric motors, whose own working field provide magnetic levitation of the rotor (without the need for external magnetic bearings), have been referred to in literature as "bearingless motors".

1) Complete Magnetic Suspension: In this case the magnetic levitation system controls the rotor movement in all five degrees of freedom (The sixth degree of freedom being axial rotation). Auxiliary conventional bearings provide support only when there is no power supplied to the magnetic suspension system.

2) Partial Magnetic Suspension: Partial magnetic suspension with respect to individual degrees of freedom simplifies considerably the magnetic support's design. The other degrees of freedom are restricted by conventional bearings. As an example axial magnetic support with radial gas dynamic bearings or radial magnetic support with axial journal bearings.

3) Magnetic Relief: Magnetic relief is when restriction of the rotor's movements is accomplished entirely by mechanical, gas or hydrodynamic supports, and the magnetic field is used only to compensate mechanical loads acting on these supports. It is used in hydrogenerators for relieving an oil bearing from the rotor's gravitational forces, and also in micromotors for relieving ball-bearing supports from forces of one sided magnetic attraction (UMP).

Chiba et al. [5-7] have proposed a partial magnetic suspension "bearingless" four pole induction motor with separate two pole windings. The four pole windings are supplied by symmetrical currents and are responsible for the electric motor's torque. The two pole winding currents are regulated by radial position controllers to produce the radial forces. This control is achieved by having a weak two pole rotating magnetic field winding pattern which introduces a controllable two pole field in addition to the normal four pole field. A net vertical force is produced from the interaction of the two air gap fields with the purpose of relieving the weight of the rotor impressed on the bearings.

II. MOTOR WINDING DISTRIBUTION AND RADIAL FORCE EXPRESSION

The motor proposed in this research achieves magnetic levitation based on the same concept outlined in [5-7] without adding any extra windings to the stator. The conventional four pole winding of the machine is utilized to obtain the effect of equivalent four pole and two pole windings simultaneously. In this case the machine requires six terminals as illustrated in Fig. 1 for a 36 slot 60^{o} phase belt double layer winding. Each two of the four coil groups per phase are connected to form two independent windings per phase resulting in a six stator winding machine. The labeling of the six stator coupled circuits is chosen as 1 - 6 to avoid associating each with a certain phase since the same coupled circuit can have two currents belonging to two different phases for each of the equivalent windings as will be shown next. Defining the winding function as the MMF spatial distribution for one ampere of current [8], the stator circuits normalized winding function $N_i(\phi_m)$ of each of the six stator windings can be plotted as shown in Fig. 2.

Applying the principle of virtual displacement, it was shown in [9, 10] that the net radial electromagnetic force acting on the rotor can be expressed in terms of the actual coupled circuits variables. For a concentric rotor and stator, the horizontal and vertical components of this force are defined as:

$$F_x = \frac{1}{2}[I]^T \frac{\partial[L]}{\partial x}[I]$$

$$= \frac{1}{2g}[I]^T [Kx][I]$$

(1a)

$$F = \frac{1}{\ }[I]^T \frac{\partial[L]}{\ }[I]$$

$$Kx_{ij} = \frac{\mu_o rl}{g}\int_0^{2\pi} N_i(\phi_m)N_j(\phi_m)\cos(\phi_m)\,d\phi_m \qquad (2a)$$

$$Ky_{ij} = \frac{\mu_o rl}{g}\int_0^{2\pi} N_i(\phi_m)N_j(\phi_m)\sin(\phi_m)\,d\phi_m \qquad (2b)$$

ϕ_m: angular position along the stator inner surface (mech. rad).
r: outer radius of rotor or inner radius of stator
l: axial length of the machine
g: air gap length
N_i and N_j: winding function for coupled circuits i and j respectively
x and y: are the horizontal and vertical directions respectively

Several assumptions effect the accuracy of the net radial force calculations based on expressions (1) and (2). A magnetically linear model is assumed, secondary effects due to stator slotting are ignored, and eddy current effects are also ignored.

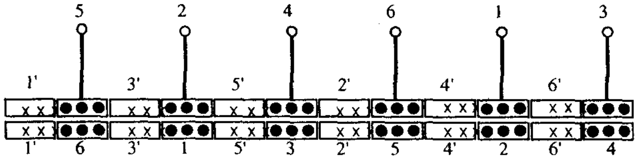
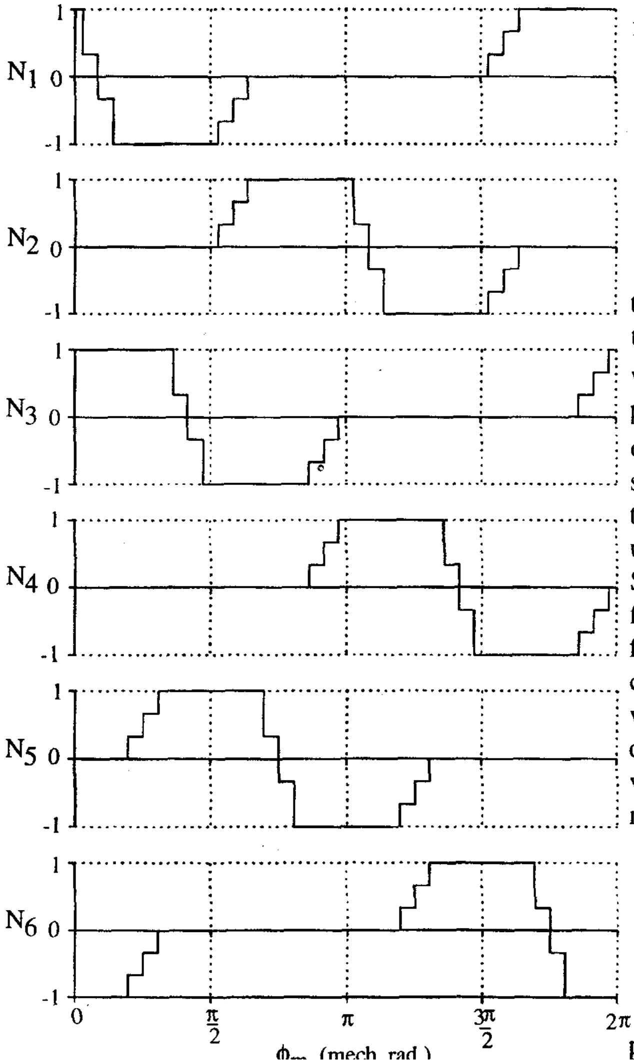


Fig. 1 Winding distribution for four pole machine with 60^{o} phase belt

III. FOUR POLE AND TWO POLE EQUIVALENT WINDINGS OBTAINED FROM A CONVENTIONAL FOUR POLE WINDING

Each stator coupled circuit has two superimposed currents flowing in it. The first current is the "main" four pole current (i_a or i_b or i_c) responsible for torque production while the second is the "control" two pole current ($i_{a'}$ or $i_{b'}$ or $i_{c'}$) responsible for the production of radial electromagnetic force. To achieve both a four

$$
\begin{aligned}
i_1 &= i_a + i_{a'} \\
i_2 &= i_a - i_{a'} \\
i_3 &= i_b - i_{c'} \\
i_4 &= i_b + i_{c'} \\
i_5 &= i_c + i_{b'} \\
i_6 &= i_c - i_{b'}
\end{aligned}
\qquad (3)
$$



the same current flows in two different coupled circuits then this is equivalent to connecting them in series. Thus an equivalent coupled circuit can be obtained whose winding function is the summation of those two coupled circuits winding functions. The equivalent three phase four pole winding functions would be defined as:

$$
\begin{aligned}
N_a &= N_1 + N_2 \\
N_b &= N_3 + N_4 \\
N_c &= N_5 + N_6
\end{aligned}
\qquad (4)
$$

The equivalent normalized two pole winding functions are:

$$
\begin{aligned}
N_{a'} &= N_1 - N_2 \\
N_{b'} &= N_5 - N_6 \\
N_{c'} &= N_4 - N_3
\end{aligned}
\qquad (5)
$$

Figure 4 shows these winding functions as having two poles over the entire rotor periphery. Notice that the magnetic axis for phase a is the same as for winding 1 (-30° mech.) in case of the equivalent four pole winding but is spatially shifted in case of the equivalent two pole winding (-75° mech.). The spatial shift of the equivalent two pole winding functions is due to the occurrence of flux cancellation in slots where the upper and lower coil sides belong to different windings. Since the equivalent two pole current is a very small fraction of the total slot current, the extra losses due to flux cancellation should be minimal. The flux cancellation also results in the equivalent two pole winding having the same (instead of twice the) number of turns per pole per phase as the equivalent four pole winding as verified by comparing the amplitudes of the normalized winding functions of Fig. 3 and Fig. 4.

IV. RELATIONSHIP BETWEEN FORCE COMMANDS AND CURRENT REFERENCES

Force command components F_x^* and F_y^* must be predefined to accomplish magnetic relief for the rotor.

winding current commands from F_x^* and F_y^*, a linear relationship of F_x and F_y as functions of these actual currents has to be derived first and then inverted to obtain the currents as functions of the forces.

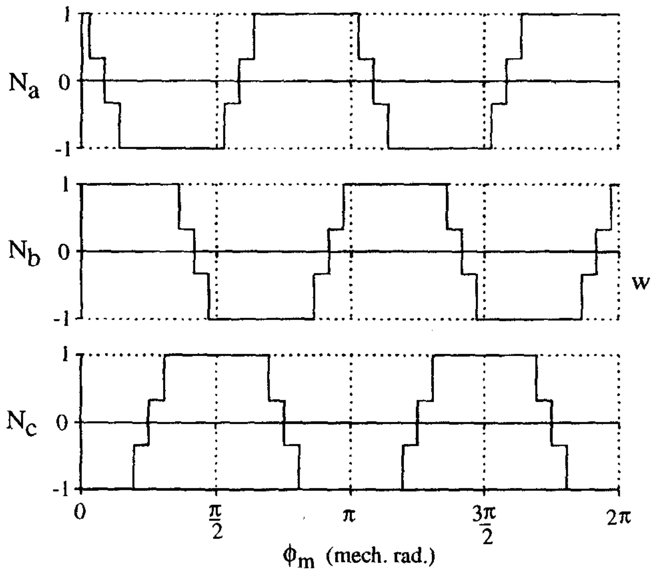
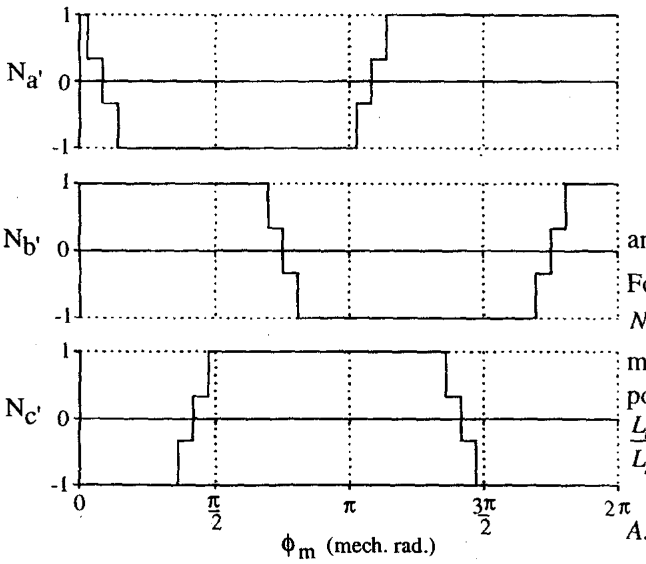


Fig. 3 Equivalent four pole normalized winding functions



distribution are ignored. Thus only the fundamental components of the winding functions of Fig. 3 and 4 are used. This restriction facilitates the use of linear transformations to obtain two phase instead of three phase equivalent four pole and two pole windings. The two phase winding functions are defined as:

$$\begin{aligned} N_u &= N_{4p}\sin(2\phi_m) \\ N_v &= -N_{4p}\cos(2\phi_m) \\ N_\alpha &= N_{2p}\cos(\phi_m) \\ N_\beta &= N_{2p}\sin(\phi_m) \end{aligned} \tag{6}$$

where:

N_{4p} : effective number of series connected turns for the equivalent four pole winding $= \frac{4}{\pi} k_{w4} N_{ser}$

N_{2p} : effective number of series connected turns for the equivalent two pole winding $= \frac{4}{\pi} k_{w2} N_{ser}$

N_{ser} : total number of series turns per phase

k_{w4} : winding factor for equivalent four pole winding

k_{w2} : winding factor for equivalent two pole winding

The equivalent 4 pole windings are labeled $(u \,\&\, v)$ and the equivalent 2 pole windings are called $(\alpha \,\&\, \beta)$. For a 36 slot, full pitch winding (Fig. 1), $N_{4p} = 1.22\,N_{ser}$, while $N_{2p} = 1.26\,N_{ser}$. Hence, assuming magnetic linearity, the ratio between the equivalent two pole and four pole windings magnetizing inductance is $\frac{L_{m2}}{L_{m4}} = 1.06$.

A. Under No-load Condition

Neglecting time harmonics, there is no current

By carrying out the integrations of (2) on the equivalent two phase winding functions of (6), $[Kx]$ and $[Ky]$ are calculated to be:

$$[Kx]=\frac{u_0 r l}{g}N_{4p}N_{2p}\begin{bmatrix} 0 & 0 & 0 & \frac{\pi}{2} \\ 0 & 0 & -\frac{\pi}{2} & 0 \\ 0 & -\frac{\pi}{2} & 0 & 0 \\ \frac{\pi}{2} & 0 & 0 & 0 \end{bmatrix} \quad \text{(8a)}$$

$$[Ky]=\frac{u_0 r l}{g}N_{4p}N_{2p}\begin{bmatrix} 0 & 0 & \frac{\pi}{2} & 0 \\ 0 & 0 & 0 & \frac{\pi}{2} \\ \frac{\pi}{2} & 0 & 0 & 0 \\ 0 & \frac{\pi}{2} & 0 & 0 \end{bmatrix} \quad \text{(8b)}$$

Hence, by substituting (8) in (1), the horizontal and vertical components of the net radial force are computed as:

$$F_x = M(i_u i_\beta - i_v i_\alpha) \quad \text{(9a)}$$

$$F_y = M(i_u i_\alpha + i_v i_\beta) \quad \text{(9b)}$$

where :

$$M = \frac{1}{g}\frac{\mu_0 r l}{g}N_{4p}N_{2p}\frac{\pi}{2}$$

Assuming balanced sinusoidal supply to the equivalent four pole winding:

$$i_u = I\cos(\omega_e t) \quad \text{(10)}$$
$$i_v = I\sin(\omega_e t)$$

The forces become:

$$\begin{bmatrix} F_x \\ F \end{bmatrix} = MI\begin{bmatrix} -\sin(\omega_e t) & \cos(\omega_e t) \\ \cos(\omega_e t) & \sin(\omega_e t) \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{MI}\begin{bmatrix} -\sin(\omega_e t) & \cos(\omega_e t) \\ \cos(\omega_e t) & \sin(\omega_e t) \end{bmatrix}\begin{bmatrix} Fx^* \\ Fy^* \end{bmatrix} \quad \text{(12)}$$

Two observations can be obtained from (12), at no-load:

- F_x and F_y are linearly proportional to the four pole current magnitude for constant two pole current
- F_x and F_y are independent of rotor speed

B. Modifications for Loaded Condition

When currents flow in the rotor bars, the relationships between F_x, F_y and the two pole currents become non linear. By running simulations at different speeds and slip frequencies, it was observed that loading the machine has two effects on the value of resultant radial forces:

- A decrease in the magnitude of resultant force due to rotor currents.
- A delay in the resultant force vector with respect to the force command.

These two effects can be explained by the fact that the net radial force is a result of the coexistence of the four pole and two pole air gap (magnetizing) flux components. For a constant stator current, loading an induction motor results in both a decrease in the magnitude and a phase delay in the magnetizing current component. Simulations have indicated that these effects depend only on slip frequency for the same four pole and two pole equivalent winding currents.

Figure 5 depicts the resultant force attenuation on load $k_{s\omega_e} = \frac{F}{F_{@s\omega_e=0}}$ as a function of slip frequency. Figure 6 shows the required phase advance on load (ϕ_{con}) for two pole currents to obtain a resultant force in the same direction as the force command. Thus the two pole current command (12) is adjusted to include the loaded condition and becomes

$$\begin{vmatrix} i_\alpha^* \\ i^* \end{vmatrix} = \frac{1}{MIk_{s\omega_e}}\begin{bmatrix} -\sin(\omega_e t - \phi_{con}) & \cos(\omega_e t - \phi_{con}) \\ & \end{bmatrix} \begin{vmatrix} F_x^* \\ F^* \end{vmatrix}$$

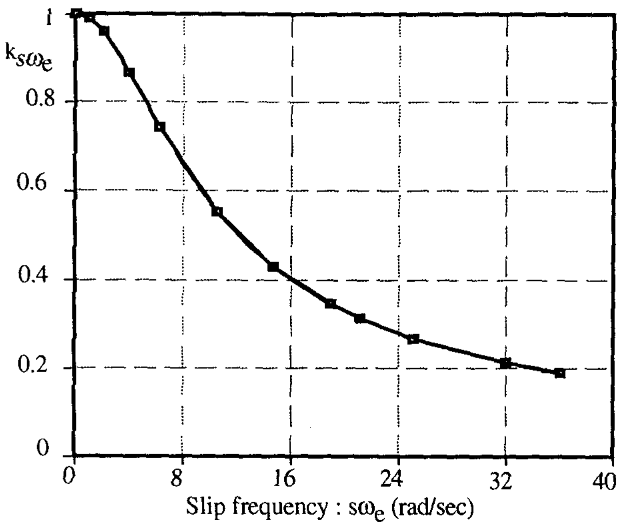


Fig. 5 Force attenuation for loaded condition

C. Two Phase to Three Phase Transformations

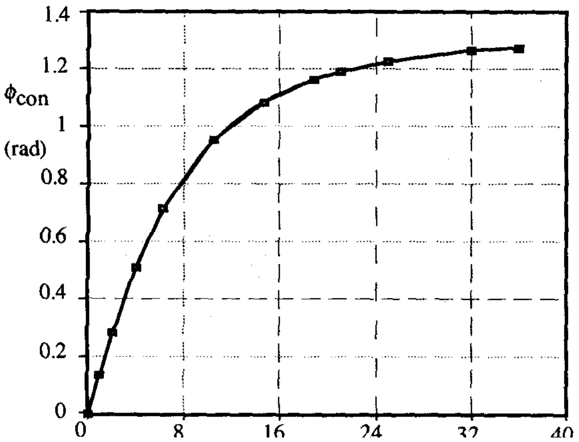
After obtaining the equivalent two phase winding current commands using (13), two phase to three phase transformations are needed for both two pole and four pole. The transformations are based on the two phase winding functions defined by (6) with the magnetic axes of the three phase winding functions obtained from Fig. 3 and Fig. 4. For the equivalent four pole windings:

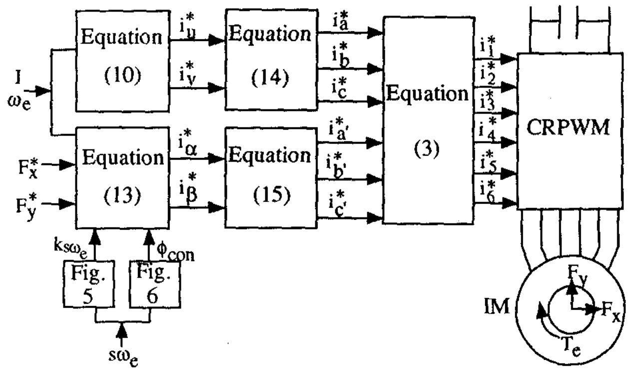
$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} -\frac{\sqrt{3}}{2} & -\frac{1}{2} \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_u^* \\ i_v^* \end{bmatrix} \qquad (14)$$

For the equivalent two pole windings:

$$\begin{bmatrix} i_{a'}^* \\ i_{b'}^* \\ i_{c'}^* \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{6}-\sqrt{2}}{4} & -\frac{\sqrt{6}+\sqrt{2}}{4} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ -\frac{\sqrt{6}+\sqrt{2}}{4} & \frac{\sqrt{6}-\sqrt{2}}{4} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \qquad (15)$$

The overall sequence for obtaining the six terminal machine current references from the force commands is depicted by the block diagrams in Fig. 7. It should be noted that the force commands and the actual resultant forces are not instantaneously equal due to the existence of spatial harmonics (caused by non-sinusoidal winding distribution, slotting and magnetic saturation) and the time harmonics (caused by the inverter supply) in the actual physical system.





and analytically verified a new strategy for alleviating the stress imposed on the bearings by producing a partial magnetic support of the rotor weight. In contrast to previous investigators, this strategy uses only the main power windings of the electrical machine itself and employs current control of two coordinated solid state power converters to produce a prescribed vertical force to counteract the weight of the shaft. Since this force can be produced even at zero speed, it should be possible to appreciably increase bearing life by aiding the bearing during the starting phase when the bearing is not well lubricated as well as during continuous operation.

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APPENDIX

Machine parameters used in the Simulation study:

Per phase parameter	4 pole connection	2 pole connection
Stator resistance	0.453 Ω	0.422 Ω
Rotor resistance	0.281 Ω	0.277 Ω
Stator leakage induct.	1.31mH	1.15 mH
Rotor leakage induct.	1.31mH	1.15 mH
Unsat Magnetizing Induct.	40 mH	79 mH