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AC POLYPHASE SELF-BEARING MOTORS WITH A BRIDGE CONFIGURED WINDING

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ABSTRACT

The designs of self-bearing motors can be broadly categorised into two groups, namely: dual winding configurations; and single winding configurations. There are disadvantages associated with each of these winding schemes, such as poor specific power rating and the necessity of a high number of inverter switches of high current and voltage rating. This paper presents a novel concept of winding for self-bearing motors based on a bridge connection for polyphase rotating electrical machines. Its advantages include: relatively low power loss for a given performance; only one motor inverter is required for torque production and lateral forces are produced by using auxiliary power supplies of relatively low current and voltage ratings; and many variants such as concentrated or distributed windings can be derived. The bridge connection scheme has been verified to exhibit the characteristics of a self-bearing motor via a coupled-field finite element analysis. A comparison of power loss with conventional designs is also included to support the newly proposed connection as a potential alternative to present designs.

INTRODUCTION

A self-bearing motor is an electromagnetic machine that produces torque and supports its own rotor by way of magnetic forces. The principle of magnetic force production in a self-bearing motor is to create an unbalanced flux distribution in the air gap by supplying additional levitation currents to the windings. Accordingly, various winding schemes have been proposed to accomplish the task of force production. One traditional method is to incorporate a second set of windings to carry the additional levitation currents [1], [2]. While such a method offers simplicity in control, it inherently suffers from high power loss for a given performance and requires extensive additional manufacturing effort to accommodate secondary windings. Designs using a single set of windings have also been put forward where the levitation currents are superimposed on the motor currents within the same set of windings [3], [4]. Although these machines are more efficient than their dual set of windings counterpart, they require a high number of inverter switches of high current and voltage rating. In addition, the manner in which these self-bearing motors are controlled is somewhat complicated.

This paper outlines how a bridge-configured winding can be implemented in AC self-bearing motors and the characteristics are verified via electric circuit coupled finite element simulations. It is not the aim, however, to optimise the motor design or explore its performance limits since these involve detail work. The scheme is then compared with conventional single and dual winding schemes in terms of power loss for a given performance. The advantages of such a scheme conclude the discussion of the paper.

PRINCIPLE OF OPERATION OF A BRIDGE CONFIGURED WINDING

The proposed stator winding comprises a number of independent phases with each phase split into two parallel groups. Since all electrical machines have distinct phases with two ends to every phase, we can consider only one phase as shown in figure 1 [5]. The principal feature of the bridge connection is that a supply current divided between parallel paths "CAD" and "CBD" is responsible for torque production. Another supply connected at the mid points of each path in the bridge provides the current which will be responsible for lateral forces. The bridge connection is essentially a single set of windings which carry both categories of current simultaneously.

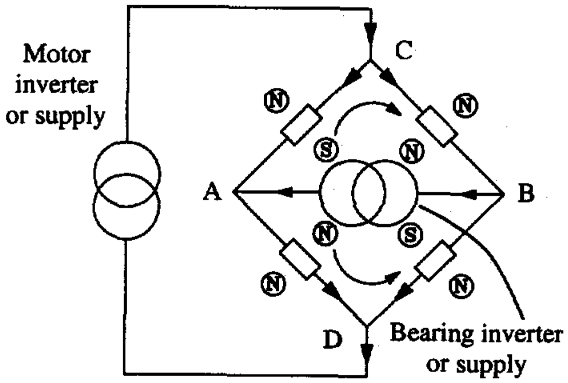

FIGURE 1: A fundamental bridge-like connection in one phase of the new self-bearing motor.

Hereafter the terms "motor inverter" and "bearing inverter" will be used to mean the power supplies for producing torque and lateral forces respectively. Furthermore, the term "levitating" or "levitation" will be used frequently to mean producing a lateral force.

Since the levitating current is much smaller than the motor current, the voltage drop across "AB" is expected to be very small compared to the full voltage rating of the phase "CD". If the impedances of branches CA, CB, AD, BD of the bridge are the same, then the voltage drop across CD is independent of the current through AB and vice versa. Such a property is exploited to produce levitating forces when an additional current is supplied at midpoints AB.

Referring back to figure 1, the magnetic polarities as a result of motor and levitation excitations are labelled at the exterior and interior of the bridge respectively. It can be seen that when the motor current is supplied at CD, all coils produce the same N polarity. However, when a levitating current is supplied, branches CA and BD have an S polarity because of the reversal in current flow. Thus, it is evident that parallel branches CA and BD will always have the same current reversing attribute but in the opposite direction to the parallel branches CB and AD. To see the usefulness of such a connection, the fundamental bridge connection in figure 1 must be extended to permit generation of the necessary motor and levitation fields in the air gap. Two variants of extension are presented in this paper, i.e. concentrated and distributed winding schemes. At this juncture we consider the self-bearing motors to be a 4-pole generic machine with an additional 2-pole field to exert a net lateral force on the rotor.

BRIDGE CONFIGURED CONCENTRATED WINDING

A 3-phase self-bearing motor having concentrated coils wound on a 12-tooth stator is shown in figures 2 - 4. Figure 2 illustrates that the coils are connected such that 2 bridges are formed per phase and therefore a total of 6 bi-directional power supplies are required for the self-bearing function. The polarities caused by the instantaneous motor and levitation currents are labelled at the exterior and interior of the bridge respectively. The first bridge of phase "a" is first studied. Coil-pairs "a11"-"a12" have the same levitation current reversing attribute and they are of the opposite polarity to coil-pairs "a13"-"a14". Thus, coils "a11" and "a12" at the first bridge of phase "a" are stacked up and aligned at the same axis of symmetry on the same stator tooth. Likewise, coils "a13" and "a14" of the first bridge are grouped together and wound at the diametrically opposite tooth.

The first bridge of phase "a" produces an N polarity when a positive motor current flows while the second bridge produces an S polarity. In a similar manner, coils in phases "b" and "c" are connected to form an overall 3-phase, 4-pole self-bearing motor. In general, the same magnitude and direction of flux density at diametrically opposite stator teeth will produce a symmetrical 4-pole field, whereas the same magnitude but opposite direction of flux density at diametrically opposite teeth will produce a symmetrical 2-pole field. The bridge connection plays a role of producing the required 4-pole motor field and a 2-pole levitation field when the motor and levitation currents flow as shown in. figures 3 and 4.

BRIDGE CONFIGURED DISTRIBUTED WINDING

An alternative variant that produces an equivalent distributed flux density to that of a conventional 4-pole motor is depicted in figure 5. Note that the usual convention of crosses and dots are used to indicate current flowing in and out of the slots respectively. The coils are wound in a 24 slots stator and resemble a double layer distributed winding. Coil sides "a1" and "a11" constitute a single coil where the conductor goes into slot "a1" and returns via slot "a11" making a number of turns. Any injection of current in one coil side will result in an opposite direction of current flow in the other coil side. A coil linking slots "a3"-"a33" are connected in parallel to the aforementioned coil because both coils have the same current reversing attribute. Similarly the coil linking slots "aa2"-"aa22" are connected in parallel to another coil linking slots "aa4"-"aa44" and together with coils "a1"-"a11" and "a3"-"a33" they form the first bridge of phase "a". A second bridge is connected in a similar fashion and so a total of 8 coils are required to fill phase "a" slots.

When all phases are connected as described, the instantaneous motor and levitation currents as shown in figure 5 produce the 4-pole motor and 2-pole

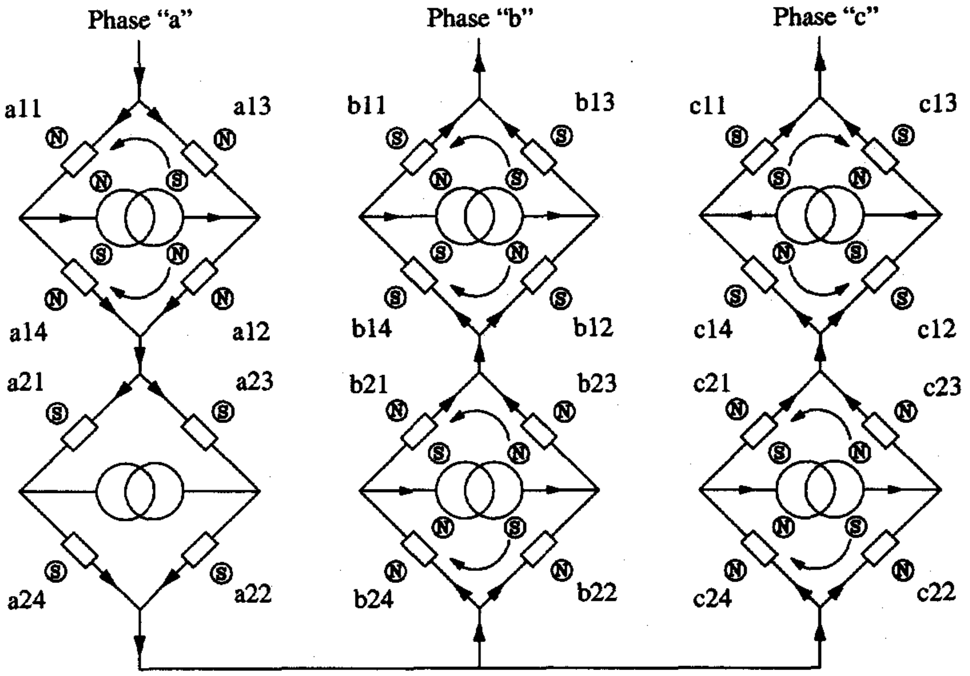

FIGURE 2: Instantaneous motor and levitation currents in the bridge configured concentrated winding scheme producing the fluxes in figures 3 and 4.

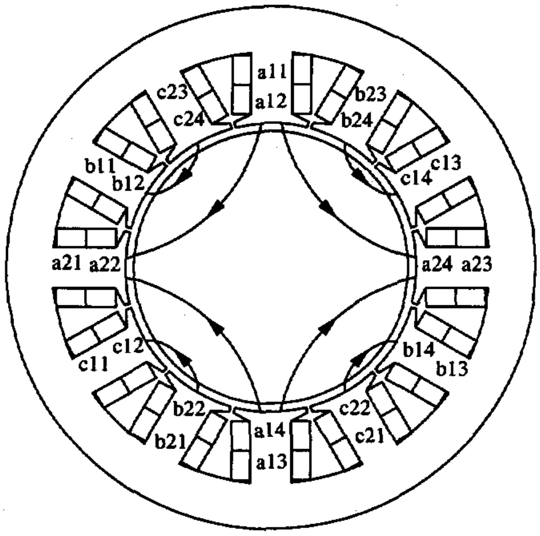

FIGURE 3: Bridge configured concentrated winding producing a 4-pole motor field

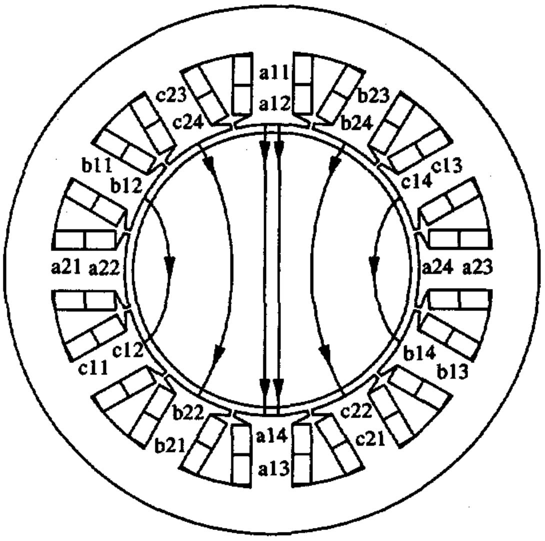

FIGURE 4: Bridge configured concentrated winding producing a 2-pole levitation field

levitation fields in figures 6 and 7 respectively. The present variant scheme has an improved sinusoidal flux distribution compared to the concentrated winding scheme because of the increased number of stator slots and the distributed nature of the slot current densities. However, the present scheme may not create a 2-pole levitation field as perfectly as its 4-pole motor field because of the way it is connected. For example, when all phases are excited, the resulting levitation field will have a slight notch at its maximum peaks. Despite this minor imperfection the overall levitation field still resembles a sinusoidal waveform and thus, a net lateral force can be achieved. What is important is that at least two levitation m.m.f. axes must be generated so that the linear combination of both m.m.f.s will give a net lateral force in any arbitrary direction.

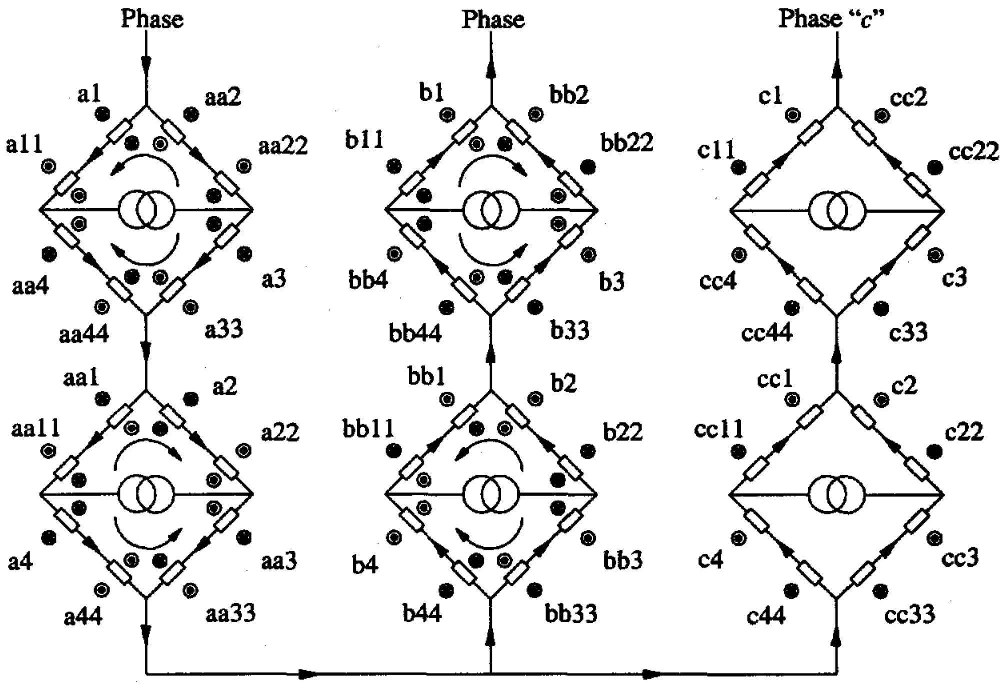

FIGURE 5: Instantaneous motor and levitation currents in the bridge configured distributed winding scheme producing the fluxes in figures 6 and 7.

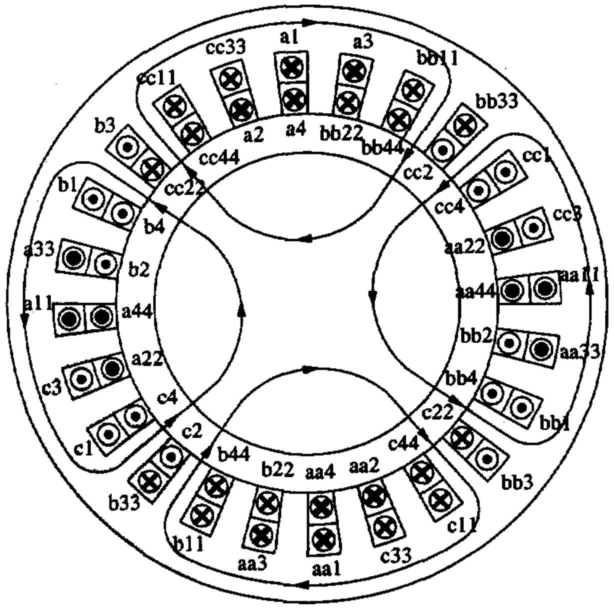

FIGURE 6: Bridge configured distributed winding producing a 4-pole motor field

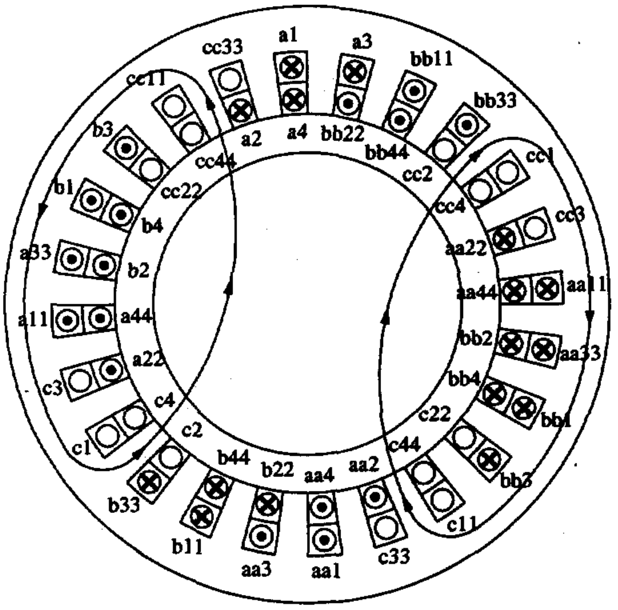

FIGURE 7: Bridge configured distributed winding producing a 2-pole levitation field

ELECTRIC CIRCUIT COUPLED FINITE ELEMENT ANALYSIS

A surface mounted permanent magnet (PM) self-bearing motor with a bridge configured concentrated winding was chosen for the purpose of verification. It has the following physical properties: PM remanence: 0.95 T; magnetic coercivity: 6.8E5 A/m; PM thickness: 2 mm; rotor radius, *r*: 30 mm; stack length, *l*: 0.1 m; number of turns per tooth, *N*: 120 (2 coils of 60 turns). In a PM self-bearing motor the components of flux density that exist in the air gap are caused by the PM, motor current and levitation current, i.e. B_{PM}, B_{MC} and B_{Lev}. It is a requirement that the torque components of flux density, B_{PM} and B_{MC}, must be of a pole-pair different to the levitation flux density B_{Lev} in order for lateral forces to be produced [3]. The overall force exerted on the rotor can be evaluated approximately by summing the radial force developed at each local stator tooth (integration of normal Maxwell stresses):

$$F_{(X)n} = \frac{A_p}{2\mu_0}\sum_{n=1}^{N_S}\left[\left(\begin{array}{l}\left(B_{PM(n)}+B_{MC(n)}\right)^2\\ +2\left(B_{PM(n)}+B_{MC(n)}\right).B_{Lev(X)n}\\ +B_{Lev(X)n}{}^2\end{array}\right).\cos\theta_n\right] \tag{1}$$

$$F_{(Y)n} = \frac{A_p}{2\mu_0}\sum_{n=1}^{N_S}\left[\left(\begin{array}{l}\left(B_{PM(n)}+B_{MC(n)}\right)^2\\ +2\left(B_{PM(n)}+B_{MC(n)}\right).B_{Lev(Y)n}\\ +B_{Lev(Y)n}{}^2\end{array}\right).\sin\theta_n\right] \tag{2}$$

where n, N_S, A_p and μ_0 are the tooth number; stator teeth count; tooth area; and permeability of free space respectively. The components of flux density can be evaluated by using Ampere's loop law with appropriate equivalent m.m.f drops. Torque can be calculated from:

$$T = -\frac{p\mu_0\pi r l}{g_o}F_s F_r \sin\varphi_m \tag{3}$$

where p, g_0, F_s, F_r and φ_m are the number of pole-pairs; air gap size; maximum fundamental stator m.m.f.; maximum fundamental rotor m.m.f.; and mechanical torque angle respectively.

Torque and lateral force production are investigated by performing a 2D coupled-field finite element analysis (FEA). The coils and current sources are connected according to figure 2 and coupled to the elements of the stranded coils. This allows the excitation to be varied at ease by defining the currents of the current sources. No direct input of current density is required. As shown in figure 8, the torque is proportional to the increasing applied motor current over the selected range of excitation. Evaluating the torque constant K_T from the gradient of the non-linear plot gives 0.9 Nm/A. Levitation is simulated by increasing the levitation current so that a vertical force is exerted on the concentric rotor. The result is shown in figure 9 where the relationship is found to be linear. Evaluating the gradient of the non-linear plot gives the actuator gain of the machine, i.e. 60 N/A.

There are slight discrepancies between the analytical calculations and linear FEA due to assumptions made in the equations (uniform flux density across the tooth tip and zero tangential tip forces) and also the square waveform of the PM flux density. The FEA also confirms that increasing the levitation current does not have any effect on the torque. For a perturbation within 5 % of the maximum air gap size, the negative stiffness is found to be approximately –1E6 N/m.

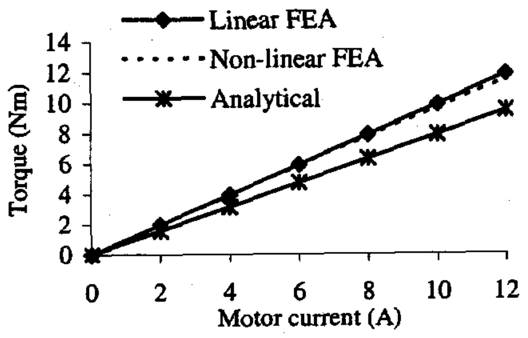

FIGURE 8: Torque characteristics

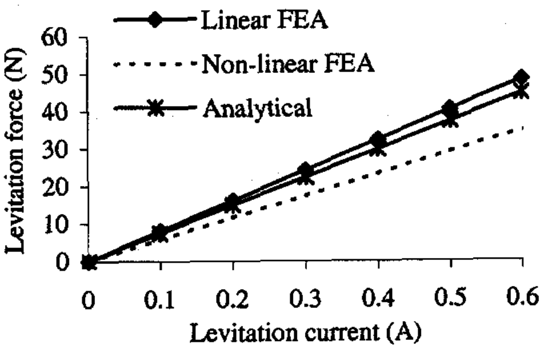

FIGURE 9: Force versus levitation current (constant motor current 8 A)

COMPARISON OF POWER LOSS WITH CONVENTIONAL DESIGNS

To make a comparison of power or copper loss for a given performance in terms of force and torque, two conventionally implemented winding schemes are considered, i.e. single set of windings (SS) and dual set of windings (DS). Both machines have the same physical dimensions (12-slot stator), total number of concentrated coil turns per tooth (120), pole number (4-pole motor & 2-pole levitation fields) and material properties as previously specified for the bridge configured winding self-bearing motor. For the SS self-bearing motor, each concentrated coil is excited by separate bi-directional power supplies to carry both torque and levitation-producing current components. Thus, this motor has a total of 12 power supplies. The primary set of windings of the DS scheme forms a

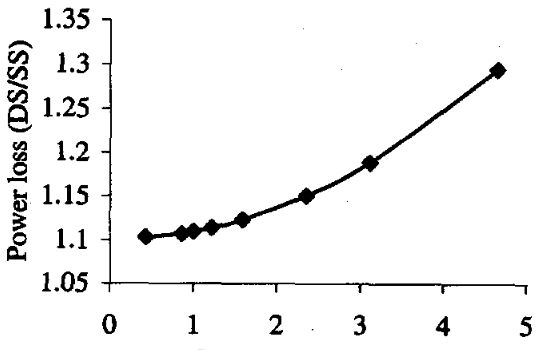

FIGURE 10: Power loss ratio (DS/SS) for a given performance (force/torque)

three-phase star connection powered by a motor inverter whereas the secondary set is connected to 2 bearing inverters for levitation control. The winding ratio between the former and the latter is 9:1.

Since the conductors in the bridge configured and the SS schemes carry both motor current (I_{MC}) and levitation current (I_{Lev}) simultaneously to give the same performance, both schemes essentially produce the same total copper loss, which can be evaluated analytically from:

$$P=\sum_{n=1}^{N_S}\begin{bmatrix} I_{MC(n)}{}^2+I_{Lev(n)}{}^2+ \\ 2I_{MC(n)}I_{Lev(n)}\cos\left(\pi-\gamma+\theta-\lambda+\varphi_e\right)\end{bmatrix}\frac{N\rho l N_{cs}}{2A_{cond}} \tag{4}$$

where θ, ωt, φ_e, λ, γ and A_{cond} are the angular coordinate; frequency; electrical torque angle; phase angle due to the summation of B_{PM} and B_{MC} in the air gap; the desired angle of lateral force; and cross-sectional area of an individual copper conductor respectively. The number of turns N used for the bridge configured winding is 60 whereas for the SS scheme this number is 120. N_{cs} refers to the number of coil side per tooth in which there are 4 coil sides for the former scheme and 2 for the latter. Equation (4) can be modified to calculate the total power loss for the DS scheme:

$$P=\sum_{n=1}^{N_S}\left[I_{MC(n)}{}^2 N_{MC}+I_{Lev(n)}{}^2 N_{Lev}\right]\frac{\rho l N_{cs}}{2A_{cond}} \tag{5}$$

where N_{mc} and N_{Lev} refer to the number of turns of the motor coil and levitation coil respectively.

The power loss expressions in (4) and (5) provide a very good agreement with the FEA results. Figure 10 shows how the power loss ratio of the SS (or bridge) scheme to the DS scheme varies as the per unit (pu) ratio of force to torque is increased. It is evident that the DS scheme has at least 10% more power loss than the SS scheme for any given performance. This is due to the fact that the number of turns for motoring torque has been reduced to accommodate a secondary set of windings, and so higher currents are required to produce the same magnitude of force and torque in the DS scheme. Thus, the specific power rating of the DS scheme is relatively low.

SUMMARY

Although the bridge configured winding has the same power loss as the SS scheme, the former has the advantage of needing only one standard 3-phase motor inverter. Levitation control is segregated from the torque control by employing bi-directional power supplies of relatively low current and voltage rating. This is a potential cost-saving solution since only a small amount of current is required to achieve levitation. The use of a number of small power supplies also means the system has a degree of fault tolerance. In the presence of an appropriate rotor support, such as mechanical bearing, the bearing inverters can be switched off and the machine can be operated with the motor inverter alone. The conventional motor control is preserved exactly - unlike the SS scheme. The proposed bridge connection can be easily extended by adding more bridges in each phase to enable any arbitrary combinations of poles and phases in star- or delta-connections. Moreover, the bridge connection can be manipulated to obtain many variants of concentrated or distributed windings including toroidal or Gramme ring windings. Although only the PM self-bearing motor is demonstrated as an example, the bridge connection is also applicable to various types of motors or topologies such as switched reluctance, synchronous and induction motors.

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