INDUCTION MOTOR FOR WIDE RANGE STATIC INVERTER DRIVE:
ELECTRICAL MACHINES DESIGNER'S POINT OF VIEW

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INDUCTION MOTOR FOR WIDE RANGE STATIC INVERTER DRIVE:
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ABSTRACT

A fact, usually overlooked in technical papers is that the design of electrical motors in a.c. drives is highly dependent on the parameters and construction details of the power supplying steady-state conversor, especially on the harmonic content of the applied voltage. The paper outlines some ways of making the motor less sensitive to such harmonics, even when it drives a shaft which is suspended on active magnetic bearings.

Attention was shifted from the inverter design to the induction motor design, to ways and means of making the motor immune to changes from one type of inverter to another.

The solutions presented are the result of design, manufacturing and extensive testing of a series of induction, squirrel cage electric motors, used in high performance machine-tools (boring and grinding precision machines) with rotating speeds up to 42,000 rpm, with speed control by continuous speed variation. Ratings of electric motors were 0.4; 1.1; 2.2 kw.

INTRODUCTION

A usual paper on magnetic bearings does mention the outstanding (1) qualities of a shaft rotating at high speeds floating in magnetic fields, but does not mention that the smoothness of the motor torque is an essential prerequisite. A paper on static inverters is highly concerned with the electronics but not with the noise and interference (in a larger sense) on the induction motor. There exists a sort of sectarianism, an excessive adherence and devotion to the particular matter of aforementioned papers.

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It is then the task of the motor designer to make the electrical machine shielded to the content of harmonics, which may come from the inverter, giving to the driven shaft a smooth and clean torque. In a known work of Amato \cite{2} dedicated to methods of analysing the power converter waveforms, are listed the drawbacks of the rich harmonic content in the induction motor current.

1. Higher r.m.s heating of the motor stator.
2. Increased losses due to skin effect.
3. Higher rotor iron losses.
4. Increased eddy-currents and stray load losses.
5. Harmonic torque production.

The present paper will be concerned only with the last point, because we think that a reasonable increase in losses is a small price to pay for a high quality performance and the coefficient of safety for insulation in electrical machines is lax anyway. However, it is to be stressed that parasitic torques and specially the unilateral attraction forces play a very negative role in system floating in magnetic fields, modifying the flexible shaft-tool performance in a higher degree than in the case of conventional bearings. The task is to make the motor compatible with the inverter no matter what type this inverter might be.

Robertson and Hebbar \cite{3}, as well as Kilingshirn and Jordan \cite{4}, have calculated the harmonic contribution to the average output torque coming out with relatively small numbers such as 4% for an applied six stepped voltage wave form noting however that certain inverters such as pulse-width modulated type (PWM) produce dominant harmonics at certain frequencies and their influence might be considerably larger.

Not the contribution of these harmonic to heating, not the decrease in the average torque but the parasitic torques and mainly the unilateral attraction forces are reasons of concern.

In Fig.1 is given the schematic of frequency control of an induction motor. The applied voltage is rich in time harmonics. Even if the designer would assure a sinusoidal curve for voltage, the saturation of some portions of the machine will distort the current curve. Also due to the actual layout of the windings, they are space-harmonics of the magnetomotive force which in turn produce rotor harmonics and asynchronous, synchronous torques, unilateral magnetic forces.
Fig. 1 Adjustable frequency induction motor speed control

AIR-GAP FIELD SMOOTHNESS THROUGH ROTOR SLOT AND ISTMUS DESIGN

The energy conversion (electromagnetic to mechanic) occurs at the air-gap level. There is an ideal place to filter the fields, to attenuate the harmonics.

Magnetic field computer calculations and plotting (using the TEXMAP and MODMAP finite-element computer codes [5] for static and dynamic fields calculations) have shown that using completely closed slots in the rotor, renouncing at the classical isthmus, in conjunction with semiclosed slots in the stator can smooth the airgap fields, dramatically attenuating the harmonics, exactly at the place where the electromagnetic torque is produced. Testing confirmed experimentally such results.

A copper-cladding of approximately 0.1mm would improve even more the performance. This was verified only experimentally, the finite element computer code being too coarse to catch subtle changes in a thin high conductive layer and the corresponding increase of peculiar elements in such small space neighbouring a drastic change in permeability requiring excessive computer time.

A surprise in the treatment was that the main penalty one has to pay for choosing closed slots, even with higher ferromagnetic isthmus than customary, is smaller than expected when properly calculated. The penalty is
a considerable increase of the contribution to the leakage permeance coefficient
(specific permeance= of the slot by the permeance of the iron isthmus which
replaces the air-isthmus in the semiclosed slots (compare Fig.2 and Fig.3). Such
contribution depends strongly on the magnetomotive force of the slot and is
calculated and plotted in the classical and most complete treatise on electrical
machines by Richter [6], vol. IV, p.160. The calculation is based on the
assumption that magnetic flux density lines from iron isthmus are parallel to
the rotor surface, taking into account the decrease in magnetic loading of the
tooth due to the neighboring non magnetic parallel paths.

The testing of the motor designed using such curves (Fig. 114, p.160
in Richter, v.IV) showed a substantially higher power factor than expected which
prompted a recalculation of these curves using a fine mesh in the TEXGAP finite
element program, through the option "rezone". The results were different and
are shown in the Fig. 3 in a comparison with the curves from reference [6]. The
power factor measured experimentally coincides with the values obtained through
computer. The explanation is mainly in the exact spectrum of flux lines
consideration of saturation in iron isthmus, the use of the right magnetization
curve.

(The specific permeance for the considered shape of the slot Fig.3
is $\lambda = \frac{h_y}{3a} + 0.66 + 3\gamma$. For a circular slot $h_y = 0$ then $\lambda = 0.66 + 3\gamma$).

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Fig. 2 Air-isthmus specific permeance
of the slot as a function of aspect ratio $\frac{a}{a_4}$.

Fig. 3 Contribution of iron isthmus
to the specific permeance for
closed slots.

Richter's values

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Values calculated
with f.e.m computer code.
A natural extension of the rotor with closed slots is for increasingly higher depth of the ferromagnetic isthmus which transforms it into a solid rotor (The rotor laminations are not insulated in this case, the slip frequency being small). Finzi and Paice {7}, using also the results of Mc Connel and Swerdrup {8}, show that such motor has significant advantages over conventional squirrel cage machines, when used in conjunction with solid state inverters. For the conventional squirrel cage motor the increase of frequency at the start with the aim of increasing the motor input impedance is associated with a severe penalty, the torque per square ampere being inversely proportional to the speed of travelling field {7}. In the case if a solid rotor machine an increase of the rotors resistance referred to the primary (stator) would compensate for the frequency increase.

A middle of the way solution was adopted, increasing the iron-isthmus depth, and obtaining smaller harmonic content, without the low-performance characteristics of the solid-rotor machine. Fig.5 refers to the same stator as the machine from Fig.4 but with rotor having ferromagnetic isthmus, maintaining the same dimensions and disposition of the squirrel cage. The same P.M.W. inver sor supplied both systems.
The author did not encounter until now any literature on the shafts supported and positioned by magnetic bearing, which will mention that the main concern of the designer of electrical machine which drives such system are not asynchronous or synchronous, parasitic torques produced by harmonics but the unilateral attraction forces. Such parasitic forces were the main concern in a period of four months of testing and redesigning of induction motors of 0.4 to 2.2 kW having a rotational speed up to 42,000 rpm for use in high performance machine tools (boring and grindings).

From the general theory of electrical machines, to have an interaction of two magnetic fields, either from stator, either from rotor or from both, the order of harmonics must satisfy:

\[
\nu_{5a} \pm \nu_{5b} = \pm 1
\]

following the conditions:

\[
2 + m_1(k_{1a} + k_{1b}) = \pm \frac{1}{p} \quad m_1(k_{1a} - k_{1b}) = \pm \frac{1}{p}
\]
where

\[ j_{sa}, j_{sb} \] orders of two stator harmonics interacting together

\[ m, P \] number of phases in stator number of poles

\[ k_{ia}, k_{ib} \] factors determining the order number for stator harmonics

\[ k_{ia}, k_{ib}, m, P \] are integers, and the above relations could be satisfied only when \( p = 1 \) which is our case.

Similarly, for the rotor

\[ j_{ra} \pm j_{rb} \]

following:

\[ k_2 Z_2 = -(j_{sa} \pm j_{sb} \pm 1) \]

resulting

\[ j_{ra} + j_{rb} = \pm 1 \]

and for

\[ j_{ra} - j_{rb} = \pm 1 \]

where \( j_{ra}, j_{rb} \) are the orders of two rotor harmonics interacting together

\[ Z_2 \] number of rotor slots.

From these relations we see that a force of unilateral attraction does not appear alone, always will appear a series of forces. For each \( k_{ia} \) and \( k_{ib} \) correspond two harmonics interacting together.

Essentially, we must have for the rotor a number of slots which

\[ Z_2 \pm 6 p q \pm 1; Z_2 \neq 6 p q \pm 2 p q \pm 1 \]

in order to avoid unilateral attraction forces for \( k_2 = \pm 1 \)

Of course, the situation could be spectacularly improved for skewed rotor slots.

In lengthy testing was found that for all ratings used the most favourable number of slots for the rotor was 32, at a skewing angle less than a slot-pitch \( 6^\circ 45' \), for a number of slots of the stator of 24. The second favourable number was 28, at the same relative skewing angle, referred to the slot pitch. This does not match totally the number of rotor slots classically recommended (6)

\[ p = 1 \]

\[ Z_1 = 24 \quad Z_2 = 28 > 16 \]

For sake of curiosity, our findings were the double of Lund's
recommendation 8: \[ Z_2 = (6q_1 + 4)P \]

where \( q_1 \) = number of stator slots per pole and phase giving 16 which is the second Richter's choice.

CONCLUSIONS

In the special case of squirrel cage induction motors fed from solid state inverters, there are ways to make each machine less sensitive to the harmonic content of the power supply and even to the space harmonics due to the physical layout of the windings. The most important is to use closed slots for the rotor, with ferromagnetic isthmus thicker than usual. Performance is improved if thin copper cladding is applied over the rotor. This particular construction makes the machine slide its parameters towards the solid-rotor induction machine maintaining the good power factor and good efficiency (The solid rotor induction machine itself is not such a bad choice for inverter drive).

For rotors suspended and positioned by active magnetic bearings the unilateral attraction forces are matter of concern, parasitic torques (asynchronous and synchronous) being less important. A number of rotor slots and skewing were found to be an optimum for an entire zone of ratings.

LITERATURE


