Strategies and a Computer Aided Package for Design and Analysis of Induction Machines for Inverter-Driven Variable Speed Systems

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Abstract Induction machines designed for inverter-driven variable speed systems is different from those powered directly from utility power lines. In this paper, the design strategies of inverter-driven induction machines are discussed. This is followed by a description of a computer aided design and analysis package specifically for this purpose. The program package permits integration design of machines with inverters, comprehensive performance analysis, and system optimization, resulting in 20-30% more power density for the induction machine than that designed for direct utility power supplies by convention method. Design and performance analysis results are presented to substantiate the conclusions.

I. Introduction

Since the advent of modern AC variable systems, induction machine drives have been investigated extensively, resulting in many successful improvements. In these investigations, the primary concern has been given to the development of solid-state converters and control algorithms [1-4]. However, the electrical machine design has not gone any profound changes compared to the solid-state inverter counterpart within the same system. Nevertheless, recent progress in PM, switched reluctance, and synchronous reluctance machines has indicated a great potential of designing an electric machine as part of the synergistic design of the power inverter/motor package. The importance of designing a so-called inverter-driven electrical machine has been fully verified. At present, while the non-traditional machines, such as the switched reluctance and axially laminated synchronous reluctance machines have attracted considerable amount attention for variable speed systems [5-8], the traditional induction machine can not be neglected for its very low cost, simple and rugged structure, and well developed control algorithms [9,10].

To enhance the performance and reduce the cost of an induction machine drive, this paper presents the design strategies of an inverter-driven induction machine. First, the paper compares the operation conditions of an induction machine operated from an inverter, as opposed to those powered directly from commercial power lines. Design freedom gained by using inverter are highlighted. Then, the basic design strategies for an inverter-driven induction machine are explored. In particular, a set of equations are discussed to characterize the design and performance analysis of an inverter-driven induction machine. Based on these discussions, a computer program package capable of designing and conducting electromagnetic, thermal and mechanical analysis is developed. A family of parametric curves are generated to illustrate the advantages of inverter driven induction machine designs for a wide range of power ratings. A specific example is given to detail the design and performance analysis of an inverter driven induction machine as compared to that of a conventionally designed one.

II. Inverter Driven Operation Conditions and Design Strategies

The operation conditions of an induction machine driven by an inverter and the associated impact on the design of an induction machine are discussed in this section.

A. Inverter-Driven Operating Conditions

With the inverter as the power supply, an induction machine can be conveniently controlled with field orientation scheme. In the rotor field oriented reference frame, the basic equations of an induction machine are

$$i_{ds} L_m + i_{dr} L_r = \lambda_r \tag{1}$$

$$i_{qs} L_m + i_{qr} L_r = 0 \tag{2}$$

$$i_s = \sqrt{i_{ds}^2 + i_{qs}^2} \tag{3}$$

$$i_r = \sqrt{i_{dr}^2 + i_{qr}^2} \tag{4}$$

$$T_e = \frac{3}{2}\frac{p}{2} L_m i_{ds} i_{qr} \tag{5}$$

where i_s is the stator current, i_r is the rotor current and λ_r is the rotor flux linkage. Clearly, i_{ds} and i_{dr} produce the rotor flux, and i_{qs} and i_{qr} interact with the rotor flux to generate electromagnetic torque. In steady state operation, two additional equations hold

$$i_{qr} = \frac{\lambda_r}{r_r} \omega_s \tag{6}$$

$$i_{ds} = \frac{\lambda_r}{L_m}. \tag{7}$$

Then, Equation (5) can be expressed alternatively in terms of rotor resistance and slip frequency as

$$T_e = \frac{3}{2}\frac{p}{2} \lambda_r^2 \omega_s / r_r \tag{8}$$

Inspecting Equations (1) through (8), it is seen that the induction machine operation conditions are significantly altered as compared to those of a machine without inverter control. In particular, Equation (8) indicates that under constant rotor flux control the torque production is directly proportion to ω_s / r_r. Thus, for a required torque, a correct value of ω_s / r_r must be satisfied. On the other hand,

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in terms of machine efficiency and power factor, the rotor slip frequency ω_s should be minimized. To simultaneously satisfy the required torque T_e and a small slip frequency ω_s, r_r must be properly designed. The importance of controlling the value of r_r through machine design is apparent at this point.

Inverter-driven field orientation control of an induction adds other features to its operation. Note that with an adjustable frequency, an induction machine is able to move its torque-speed profile from the rated synchronous frequency to any other frequencies of interests as shown in Figure 1.

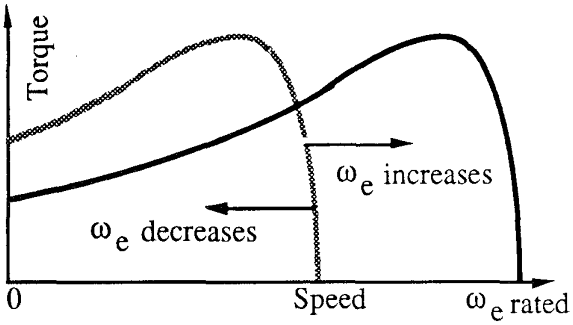

Figure 1 Torque-Speed in Variable Frequency Operation

This moveable torque-speed profile ensures that the line start-up performance of an induction machine under a fixed synchronous frequency and other considerations become unnecessary. Essentially, it is possible that the line-start torque can be replaced by the peak torque, and the rated torque can be set at a most favorable slip frequency, resulting in minimized slip power losses and stray iron losses.

B. Design Strategies

The major difference in designing an induction motor in inverter and in commercial power supply operating conditions is how to distribute design weights. In conventional design for commercial power lines, the basic considerations are placed on: i) to satisfy the needed start-up characteristics; ii) to provide appropriate steady state characteristics, emphasizing efficiency and power factor; and iii) to permit easy and economic manufacturing [10].

Items i), ii) and iii) are generally assigned a weight of 50%, 30% and 20%, respectively. The conventional design strategy implies that in a standard induction design, the primary concern is the start-up characteristics, which includes limiting inrush current, generating as much as possible starting torque, and ensuring a high starting efficiency. To meet the start-up requirements, the design strategy is searching for means to maximize the skin effect and to increase the rotor resistance during starting.

For an induction machine operated from utility line, it is necessary to solve two additional problems: a) to eliminate or minimize the harmonics produced abnormal torque occurring during start-up phase, and b) to reduce electromagnetic noise. As well-known, the solution to these two problems is to properly match rotor and stator slot numbers. Unfortunately, this solution imposes additional restrictions to the rotor design. In effect, reducing r_r so as to minimize the slip frequency ω_s as indicated by Equation (8) becomes conflicting to the starting performance.

However, in designing an inverter-driven induction machine, the strategies are very different. Weight assignments to Items i) through iii) can be entirely changed because two freedoms are gained: a) start-up current, torque and efficiency with a fixed frequency can be completely ignored; and b) abnormal harmonic torque at the time of starting will not occur and needs no consideration. Thus, it is logic to assign all design weights to Items ii) and iii). Removing the weight of Item i) implies that restrictions imposed by the stator/rotor slot combination rules and rotor slot shape can also be lifted. The design with inverter driven condition allows the stator and rotor slot numbers, shapes, and sizes to be optimized exclusively for minimizing the leakage inductance and resistance. In general, the effective utilization of rotor slot area can be increased. Consequently, the advantages associated with the reduced rotor leakage inductance and resistance, such as improved efficiency and power factor, and increased peak torque can be expected.

The new design strategy has the potential to downsize the induction machine by about one or two frame size, without sacrificing its capacity and performance. This is because the design strategy based on inverter-driven conditions emphasize the characteristics in variable frequency conditions rather than the fixed frequency start-up characteristics. In such a case, the inverter can control the induction machine being operated always at a point close to the maximum torque, maximum efficiency and improved power factor. As a result, these maximums could be introduced to the sizing equation, in place of start-up torque, the conventionally defined rated efficiency and power factor.

III. Major Equations

Many equations used for conventional induction machine design and analysis need modifications or new interpretation for inverter driven conditions and only the those related to sizing main dimensions and designing rotor laminations are discussed here.

A. Main Dimensions

The sizing equation for main dimensions applied for inverter-driven induction machines is in the form of

$$D_i^2 \ell = \frac{\xi P_o}{n} \tag{9}$$

where
D_i = stator inner diameter
ℓ = effective length of the stator stack
ξ = machine constant
P_o = rated power
n = rated shaft speed

Equation (9) directly relates the machine output torque to its volume $D_i^2\ell$. The machine constant used in the sizing equation is defined as:

$$\xi = \frac{C K_E}{K_{dps} B_g A \eta \cos\phi} \tag{10}$$

where
C = constant
B_g = magnetical loading
A= electrical loading

K_e = EMF coefficient (E/V)
K_{dps}= stator winding factor
η = efficiency
$\cos\phi$ = power factor

Equation (10) establishes the key relationship among the machine mechanical, magnetical and electrical variables. Superficially, there is little difference between the above equations and those used for a traditional induction machine design. Nevertheless, Equations (9) and (10) need alternative interpretations for an inverter driven induction machine design. Essentially, maximum efficiency and improved power factor should be used for an inverter driven induction machine because of the reasons stated in the above section. The end result is that either the volume of the machine can be significantly reduced or the power rating can be increased. Existing research and laboratory evidence has already verified these interpretations [1,3].

B. Rotor Slot and Rotor Resistance

For a conventional induction machine, it is common to design a double cage or deep bar rotor as shown in Fig. 2 to increase skin effect for large start-up rotor resistance and torque.

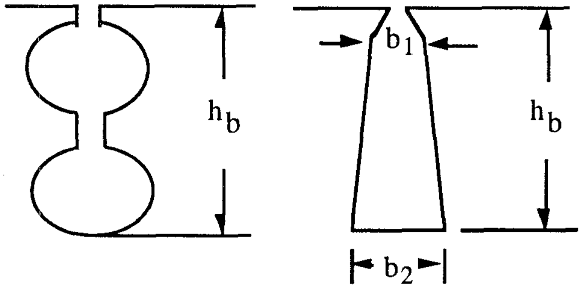

Figure 2 Rotor Slot for Conventional Induction Machines

With skin effect considered, the effective rotor resistance follows the equation

$$r_r = [\, k_r \frac{\ell_e}{\ell_b} + \frac{\ell_b - \ell_e}{\ell_b}]\, r_b \tag{11}$$

where r_b is the nominal rotor resistance without considering skin effect, ℓ_b the length of the rotor conductor, ℓ_e the effective length of the rotor core, and k_r a coefficient accounting for skin effect. Note that k_r is a function of SF as shown in Figure 3. In the figure, SF is the slot factor defined as:

$$SF = 0.1987\, h_b \sqrt{\frac{b_b\, sf}{b_r\, \rho}} \tag{12}$$

where h_b is the height of rotor conductor, b_b the width of rotor conductor, b_r the width of rotor slot, sf the slip frequency, and ρ the rotor conductor conductivity. Basically, SF relates slip frequency and the rotor slot height to the effective rotor resistance. As shown in the figure, the ratio b_1/b_2 also affects k significantly.

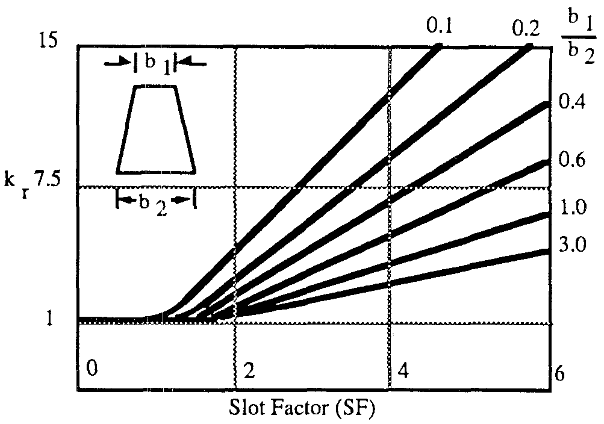

Figure 3 Relationships of k_r to the Slot Factors (SF)

In general, the deeper the rotor slot and higher slip frequency, the larger the SF and effective rotor resistance. It is seen that the line-start requirement of a conventional induction machine will result in a large SF value. Another factor affecting SF is the required speed range at a fixed frequency. For a conventional induction machine operated in a range of 0.8-0.95 synchronous speed, the rotor slot area has to be larger than that with a small slip. The larger rotor slot is chosen to avoid excessive losses when the slip is higher.

Inspecting Equations (11)-(12) and Figure 3, it can be observed that the rotor slot in a conventional design is inevitably deeper and bigger than what actually is needed, if only the rated steady state operation is considered. As discussed previously, inverter power supply is able to create such an operating condition that even the machine is continuously in a variable speed mode, it only experiences what the machine normally encountered in the rated steady state operation. Based on these considerations, an inverter driven induction machine generally favors a smaller and shorter rotor slot shape shown in Fig. 4, as opposed to the deep bar or double cage shape. The ratio $b_1/b_2 > 1$ can also be realized.

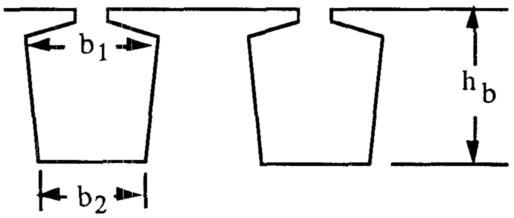

Figure 4 Rotor Slots Suitable for Inverter Driven Induction Machines

As the results, the actual area of the rotor slot can be reduced by 25-30% than that of a conventional design without increasing the effective rotor resistance.

C. Rotor Slot Leakage Reactance

As well known, the rotor leakage reactance x_ℓ of an induction machine is proportional to the leakage permeance **p**, determined by

$$x_\ell = k\,p \tag{13}$$

Figure 5 illustrates the relation of the rotor slot leakage permeance **p** to the shape of the rotor slot featured by h/b_2 and b_1/b_2.
As can be observed a deep slot (h/b2 >2) with a tip-up triangular shape (b1/b2 <0.6) has a very large **p** and, thus, substantially increases the rotor leakage reactance.

With no considerations given to the start-up characteristics, the rotor slot can be wider and shorter ($h/b_2<1.5$ and $b_1/b_2>0.9$). This results in a much reduced rotor leakage reactance. The small rotor leakage reactance, in turn, contributes to an improved power factor and increased peak torque. Combined with the reduced rotor resistance, a small leakage reactance also help reduce the slip frequency for the rated torque, and reduce the slip frequency variation for different torque levels.

IV. Computer Design and Analysis Program Package

The design strategies described in Section 2 and the alternatively interpreted design equations in Section 3 are implemented by a computer aided design package. The package is divided into two major programs: the first one deals with machine design and the second machine analysis. The overall structure of the computer program is described by the flow chart shown in Fig. 6.

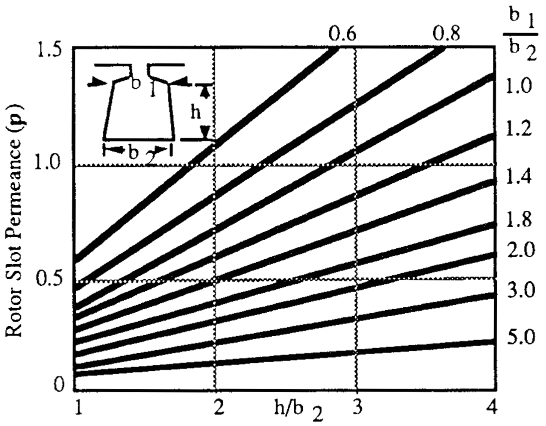

Figure 5 Rotor Leakage Permeance vs. Rotor Slot Shape

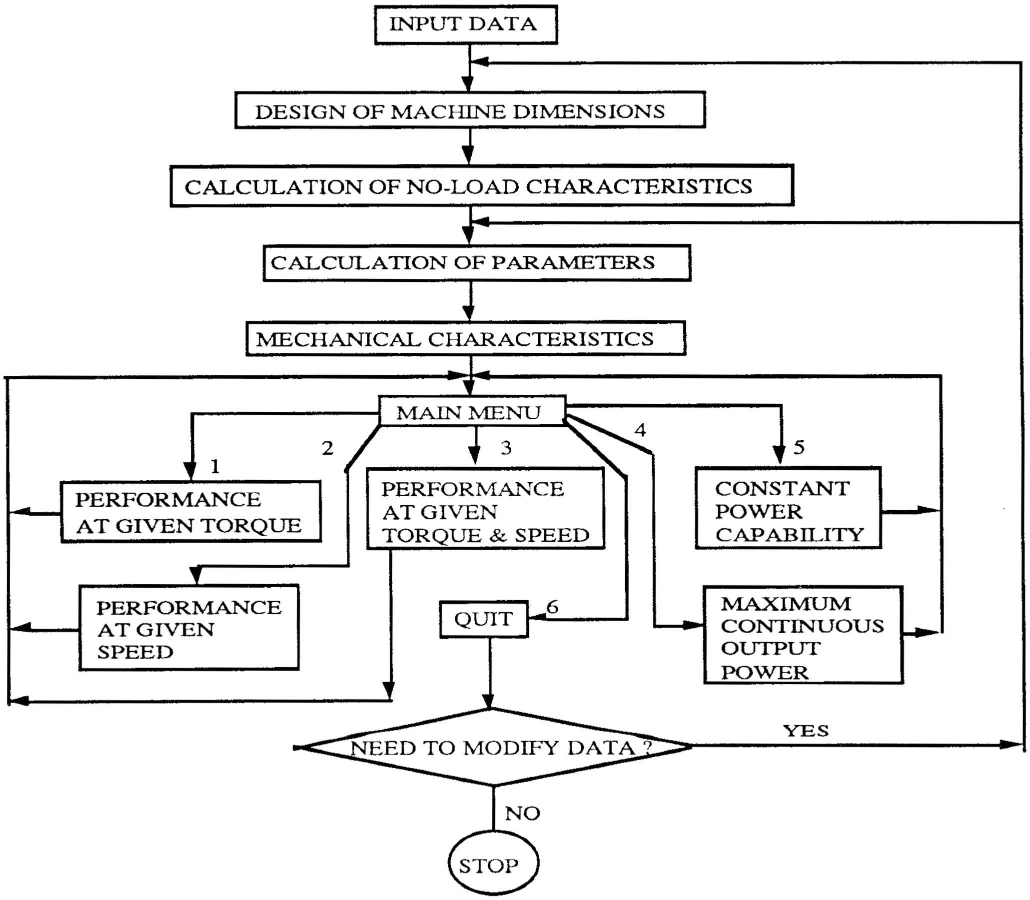

Fig. 6 Flow Chart of the Computer Aided Package for Inverter Driven Induction Machine Design and Performance Analysis

Compared to the conventional design and analysis programs, five major functions are added and implemented by the package:

a) Containing two special database for rotor slot shape selection and rotor slot leakage reactance computation;

b) Including an optimization algorithm interface the design and analysis portions for the minimized use of copper and iron;

c) Integrating an vector control algorithm into the machine performance analysis for various operating conditions, such as, performance at given torque and/or given speed, constant power capability, maximum continuous power capability, etc.;

d) Containing a sizing routine incorporating constraints of torque and speed, temperature rise, heat dissipation, component flux density levels and inverter types;

e) Generating machine parameter curves versus machine size or output power ratings (this function is based on the scaling laws and can be used for machines in normal structure. Results are presented in normalized per unit system)

It is apparent that these added functions significantly clarify the difference in designing an inverter-driven and traditional induction machine. The design and analysis capabilities of the package are greatly enhanced.

V. Design and Analysis Results

In order to substantiate the proposed design strategies and to verify the functions of the computer aided package, the design and analysis results are presented in this section. First, a family of parametric curves is generated to shown the general merits of an inverter driven induction machine. Secondly, a specific comparison is made to highlight the detailed improvement in size and performance.

A. General Characteristics Estimation

In estimating the characteristics and computing the parameters of an induction machine designed with the discussed strategies, the following parametirc curves are generated for a typical four pole induction machine under various levels of power ratings by the computer package:

a). Rotor outer diameters and percentage volume reductions versus the power ratings;

As can be seen clearly, the rated power of an inverter-driven machine design is substantially larger than that of a conventionally designed machine for the same rotor size. In the figure, the percentage volume reduction is defined as

$$\Delta V = \frac{V_1 - V_2}{V_1} \times 100\% \qquad (14)$$

where V_1 is the volume of the machine in conventional design, and V_2 in inverter driven design. The figure also indicates that along with the increase of power rating, the percentage volume reduction gets bigger and bigger. The benefits of designing a high power rating inverter driven induction machine are evident.

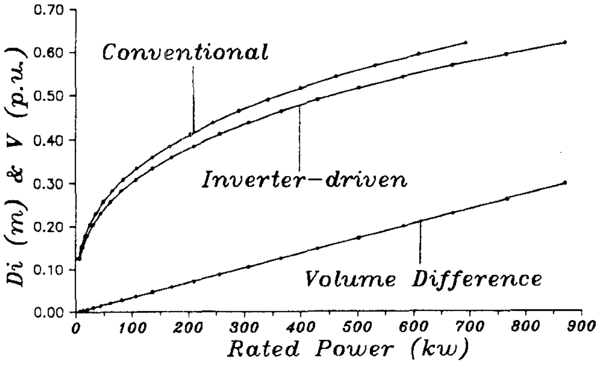

Figure 7 Rotor OD and Volume Reduction vs. Power Ratings

b) Rotor resistance and leakage reactance versus power ratings;

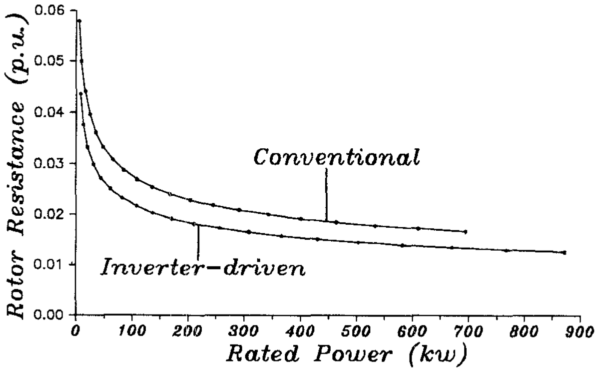

Figure 8 Rotor Resistance vs. Power Ratings

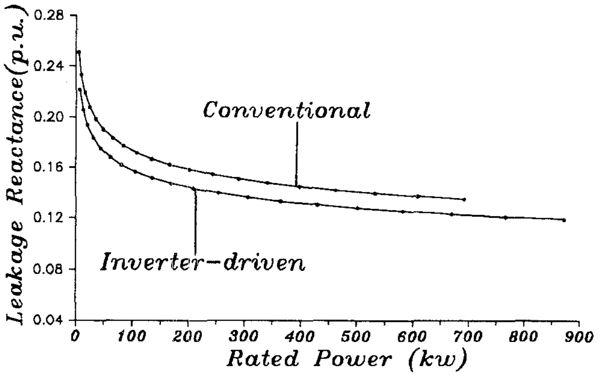

Figure 9 Rotor Leakage Reactance vs. Power Ratings

As can be observed, the rotor resistance and leakage reactance of an inverter driven machine design are smaller than those of a conventional design. The smaller rotor resistance is especially evident when the power ratings are relatively low. The difference is mainly due to the rotor slot shape change. The difference of leakage reactance is independent of power ratings.

c) Stator Resistance versus rated power

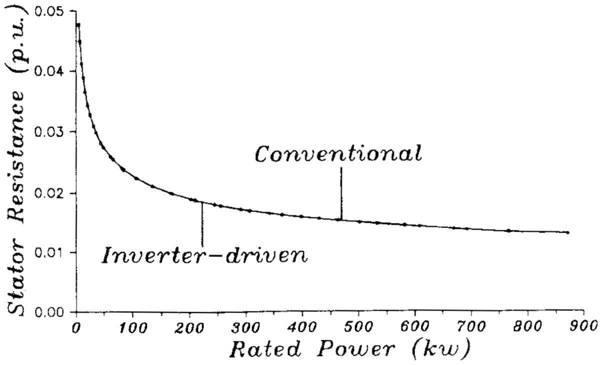

Figure 10 Stator Resistance vs. Power Ratings

Stator resistance in the two types of designs are basically the same, which indicates that an inverter driven machine design strategy seldom influences stator resistance.

d) Magnetizing reactance versus power ratings ;

For a given voltage, the maximum torque is inversely proportional to the leakage reactance and winding resistance. The maximum torque of an inverter driven machine design is larger than that of a conventional machine design, and the difference increases with the increase of the rated power.

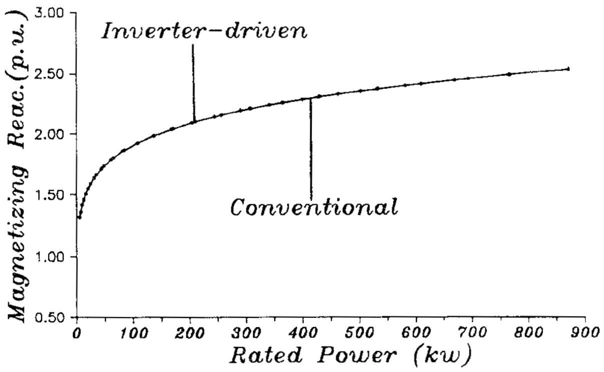

Figure 11 Magnetizing Reactance vs. Power Ratings

Similarly to the stator resistance, the magnetizing reactance of the two designs are basically the same, both increases as the rated power increases.

e) Maximum torque versus power ratings

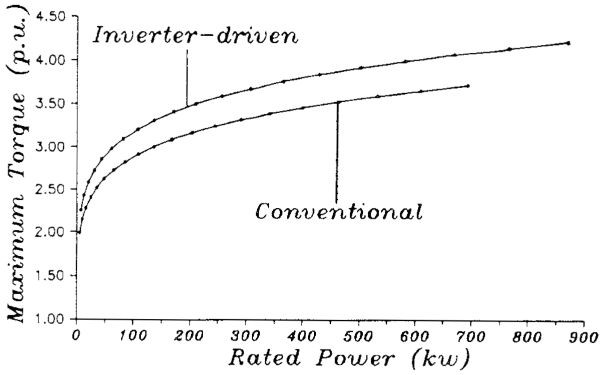

Figure 12 Maximum Torque vs. Power Ratings

f) Slip versus power ratings

Similar to the rotor resistance curve, the slip at the rated power of the inverter driven machine design is smaller than that of a conventional design. It is also seen that at low power ratings, the slip of an inverter driven machine design for rated torque is significantly smaller that of a conventionally designed machine.

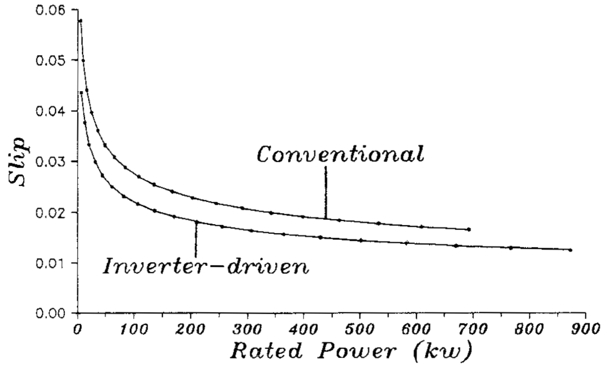

Figure 13 Slip of the Rated Torque vs. Power Ratings

B. Comparison between Two Machines

To detail the difference between an inverter driven machine design and a conventional machine design, two induction machines are designed and analyzed with the same specifications. One machine is designed using the conventional method, and the other the inverter driven machine strategies implemented by the computer package. The machine specifications are

Output power (w)	6500	Rated voltage (v)	266
Syn. speed (rpm)	800	Number of poles	4

1). Design Results

Table 1 shows the major design results of the conventional (Motor1) and the inverter-driven induction machines (Motor2).

TABLE 1

	Motor 1	Motor 2	uint
Stator OD/ID	228.9 /128	196.7/110.6	(mm)
Core Length	102.4	88.4	(mm)
ℓg /B_g	0.42 /0.87	0.36/0.90	(mm/Tesla)
Slot /surface	3.77 /162	3.83 /180	
Stator slot	36	32	
Rotor slot	28	26	
x_1/r_1	6.61 /0.68	6.23/0.69	(Ω)
x_m	127	158 (Ω)	
x_2/r_2	3.89 /0.96	3.31 /0.53	(Ω)
Stator/rotor iron	15.8 /6.5	9.5 /4.4	(kg)
Stator/rotor copper	5.9 /3.2	4.6 /2.6	(kg)

As compared to Motor1, Motor2 is noticeably smaller - the stator outer diameter is decreased by 15% and the effective length by 12%, resulting in about 25% reduction in volume. As a results, both the active iron and copper, and thus, the cost are substantially reduced in Motor2.

2). Performance Analysis

Driven by the same inverter, the performance of Motor1 and Motor 2 are analyzed and compared. Table 2 summarizes the results.

TABLE 2

	Motor1	Motor 2
T_e(p.u.) /rpm	0.826 /1800	0.825 /1800
Stator /rotor I (p.u.)	0.7 /0.69	0.69 /0.67
Input power (kw)	5.37	5.36
Basic iron loss (w)	117.0	137.7
Stray iron loss (w)	97.2	156.5
Total copper loss (w)	127 /174.1	125 /96.2
Phase voltage (v)	226.9	229.8
Efficiency/cos θ	90.4% /0.91	90.38% /0.88

It is apparent that efficiency of the two motors is almost the same, and the performance of both Motor1 and Motor2 is satisfactory for the inverter drive conditions. However, Motor2 is significantly smaller than Motor1. Equivalently, if the two motors are built of the same size, the performance of Motor2 will be better than that of Motor1.

VI. Conclusions and Future Work

The main target of designing an inverter-driven induction machine is to realize an effective synergetic inverter/machine package for high performance and low cost variable speed systems. Based on the operating conditions of an inverter drive, alternative machine design strategies are proposed. A corresponding computer aided package is developed. From analysis, calculation and example comparison we conclude that

1) The improvement of an inverter driven induction machine is mainly due to freedom gained from the line start-up performance. The design is able to be more focused on the performance in quasi-stesady state conditions;

2) Main dimensions of inverter driven induction machine are to be changed because only the most favorable operation conditions need to be considered;

3) Being freed from line-start requirement, the rotor slot number, shape, and size are to be reconsidered. The optimal design of rotor slots results in improved maximum torque, rated slip, and efficiency.

4) If an induction machine is designed in accordance with the above strategies it is possible to downsize the machine up to 20-30% without sacrificing capacity and performance;

Prototyping of the inverter driven induction machine designed by the proposed strategies and the computer aided package is in progress. Experimental data and comparison to the theoretical analysis will be reported in future papers.

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