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The Case for Induction Motors with Die-cast Copper Rotors for High Efficiency Traction Motors

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ABSTRACT

This paper considers the application of die-cast copper rotor induction motors in the drive system of parallel gas/electric hybrid vehicles and compares performance in a realistic driving scenario to that of a permanent magnet motor where efficiency is substantially reduced by PM drag loss. It is concluded from this analysis that the induction machine has a substantial advantage because it can be de-excited when it is not producing torque, eliminating no-load rotational magnetic and electrical loss.

Application of die-cast copper rotor traction motors in the hybrid drive system of the latest generation of large U.S. Army severe-duty trucks is then considered. Results of two different electric motor designs are presented, one with a cast aluminum rotor cage and one with a die-cast copper rotor cage. The copper die-cast rotor motor is shown to be 23% lighter and 30% smaller than the aluminum rotor machine.

INTRODUCTION

Current energy economics and the prospect that energy prices will be a larger item in budgets than has been the case in the past has driven governments, industry and consumers to place enhanced value on energy efficiency in general. With regard to electric motors that utilize nearly 50% of U.S. electrical energy, the United States has been a leader in passing a series of energy-saving laws over the past twenty years. The 1992 Energy Policy Act (EPAct 1992) initiated requirements for minimum motor efficiency ratings. EPACT 2005 established NEMA Premium® efficiency ratings as the basis for federal electric motor purchases and, more recently, The Energy Independence and Security Act of 2007 expands the types of motors to which efficiency standards apply and increases the efficiency minimum that a large group of commonly used motors must meet to the NEMA Premium® level. The steadily rising efficiency minimums have driven a considerable effort by both domestic and foreign motor manufacturers to redesign the induction motor to achieve these elevated efficiency minimums.

The largest energy losses in an induction motor are the I^2R losses in the stator windings and in the rotor conductor. The fraction of total full-load stator I^2R loss decreases with increasing motor size while that due to rotor conductor (about 25% of the total loss) increases slightly with increasing motor power rating. Generally the designer seeks to reduce the resistance in these conductive paths. This can mean more copper in the stator windings. In the rotor, an obvious approach was to replace the aluminum in the squirrel cage with copper to take advantage of its 60% higher electrical conductivity. This material substitution has been hampered over the years because of manufacturing problems associated with high pressure die casting of copper because of its much higher melting point.

The Copper Development Association Inc. tackled this die casting obstacle starting in 1997 to make manufacture of copper rotors both practical and cost effective. Adoption of high temperature nickel-base alloy tooling and the use of elevated temperature operation of the dies has been demonstrated to greatly increase die life [1, 2]. A number of motor manufacturers and rotor suppliers have adopted portions of this technology or are using their own technology and are now producing copper rotors on a routine basis for the industrial motor market.

This sets the stage for adoption of high efficiency induction motors for traction in electric or hybrid electric vehicles. In the demanding traction applications, copper in the rotor rather than aluminum can have size and weight advantages [3] and also has the advantages of allowing higher power densities, better heat removal and a more rigid and durable mechanical structure. In this paper first we make the case for consideration of the induction motor over a permanent magnet motor in terms of overall system efficiency. There may be a cost argument as well, but this aspect is not examined here. Next the size and performance advantages of a die-cast copper rotor induction motor in a large military vehicle are described.

INDUCTION MOTORS IN TRACTION VEHICLES

COMPARING INDUCTION AND PM MACHINES - Efficiency is as important in drive systems for hybrid electric vehicle drive motors as it is for industrial motors in manufacturing facilities and commercial buildings. Perhaps more important is motor size and weight. For these reasons, the first class of motor one would consider for vehicle drives is likely to be a permanent magnet motor using high performance magnets. With energetically 'free' excitation, low fundamental reactance and the ability to have high pole count, permanent magnet machines can be extremely light in weight and highly efficient. This is particularly true for applications that involve a restricted speed range, meaning a fixed terminal voltage. In such applications the design strategy is to build in a high internal flux (which permanent magnets do admirably), so that torque is produced with minimal input current. Then efficiency is very high, and the motor can be made light in weight and physically small.

Traction motors for applications such as automotive, are different in that they must operate over a wide speed range. Generally the requirements are thought of as requiring a certain torque ('base torque') at low speeds, up to what is called the 'base speed', and then a roughly constant power over a speed range from the base speed to a maximum speed that might be several times the base speed. In traction motor applications using wound field DC machines, this torque-speed characteristic is accomplished using what is called 'field weakening', or simply reducing field current at high speed.

The requirement for performance over a relatively wide speed range can force some compromises in permanent magnet motor design. It is not possible to turn down the permanent magnet flux to control terminal voltage at high speed. It is possible, however, to counter the permanent magnet flux with armature current, and this can be done in permanent magnet fields if the permanent magnet flux is not too strong. So permanent magnet machines built for wide speed range operation generally have relatively weak permanent magnet excitation. Then it is necessary to build a high degree of saliency into the machine so that torque can be produced by interaction of terminal current with that saliency.

Thus the permanent magnet machines built for automotive traction operation do not have all of the attractive features one would expect of permanent magnet machines. At low speed and high torque they do not really operate as permanent magnet machines: they are more akin to synchronous reluctance machines, using the interaction between saliency and (large) terminal currents to produce torque. At high speeds they employ much of their armature current capability to counter the permanent magnet flux, and this affects (negatively) efficiency at high speed. Such machines can be made to be quite efficient at relatively low torque level and intermediate speed.

In the study we describe here, we consider the drive system of Toyota's Prius hybrid automobile. The Prius motor, like other machines intended for automotive drive applications, is salient, with the rotor permanent magnets oriented in the 'direct' axis which has a reactance substantially less than that of the 'quadrature' axis.

Baseline Requirement – The drive motor we expect to emulate has a peak power rating of 50 kW, which it must be capable of over a range of 1,200 to 1,540 RPM, although the motor must be capable of withstanding rotational speeds to 6,000 RPM [4]. In the steady state, estimates of thermally limited power capability range from about 12 kW to 22 kW, depending on coolant temperature [5]. The motor is 238 mm in diameter and about 173 mm long. Efficiency at the base speed and thermally limited power is a bit less than 90%.

Table 1 – Induction Motor Specification and Estimates

	Copper Motor Rotor	Aluminum Motor Rotor	PM Rotor
Rotor Radius	78.3 mm	78.3 mm	
Active Length	88.9 mm	107.9 mm	
Stator Slot Height	22.8 mm	22.8 mm	
Rotor Slot Height	31.7 mm	37.7 mm	
Stator Back Iron	19.0 mm	19.0 mm	
Pole Count	6	6	
Number of Stator Slots	54	54	
Number of Rotor Slots	39	39	
Number of Stator Turns	108	108	
Coil Pitch	8/9	8/9	
Overall Diameter	245.9 mm	245.9 mm	260 mm
Overall Length	172.0 mm	191.1 mm	173 mm
Weight Active Material	40.7 kg	40.6 kg	
Efficiency	91 %	91%	87%
Power Factor	73%	68%	

Induction Motor - Using established design techniques, we sought to find an induction motor that could satisfy the drive system requirements as stated in the previous section, with emphasis on machine size. Induction motors have two types of limits on their operation. First, there are short-term, inductance limits on torque production, based on flux within the machine and flux produced by reaction currents. Second are thermal limits which tend to be substantially less than the peak torque limits. In this machine the peak torque limits dominated the design. Thus motors designed with both copper and aluminum rotors that could satisfy the peak torque requirements over the required speed range had somewhat higher steady state (thermal) limits than the comparison permanent magnet machine. Two induction motors that satisfy the requirements are shown in Table 1. Note the two machines have very similar weights and efficiencies, but the aluminum rotor machine is physically larger. Once the weight of a machine casing is added, this machine would be heavier as well. .

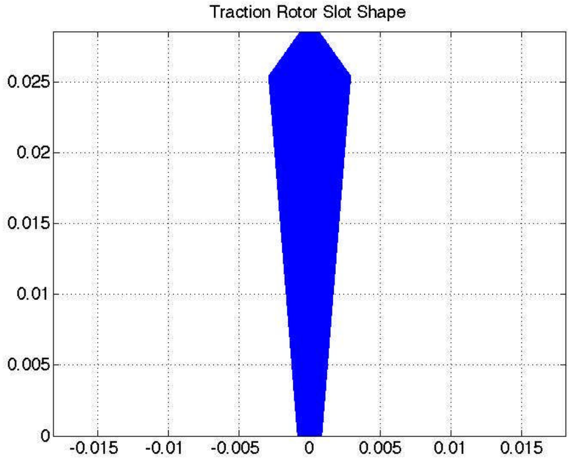

Figure 1- Traction Motor Bar Shape

Envelope numbers for the permanent magnet machine are included in the table and an estimate of efficiency, based on measurements contained in [5].

Induction Motor Performance - Torque and power capabilities for the cast copper rotor induction machines are shown in Figures 2 and 3. For this performance prediction a 'base' speed of 1600 RPM was chosen. Note the torque capability of an induction machine falls roughly as the inverse of speed squared above the base speed. This machine is capable of reaching 50 kW for speeds between about 1,200 and 2,000 RPM. At the top end of the speed range, 6000 RPM, it can reach about 20 kW.

Induction Motor Efficiency - Efficiency of the cast copper induction machine is shown in Figure 4. Note that the curves are limited by the torque capability of the machine and that efficiency stays relatively high at high rotor speeds. Efficiency is lower at low rotor speeds, as one would expect because motors are torque machines and output power is the product of torque and speed. The induction machines appear to have efficiency at least comparable to or perhaps a bit higher than the permanent magnet machine with which we are comparing them.

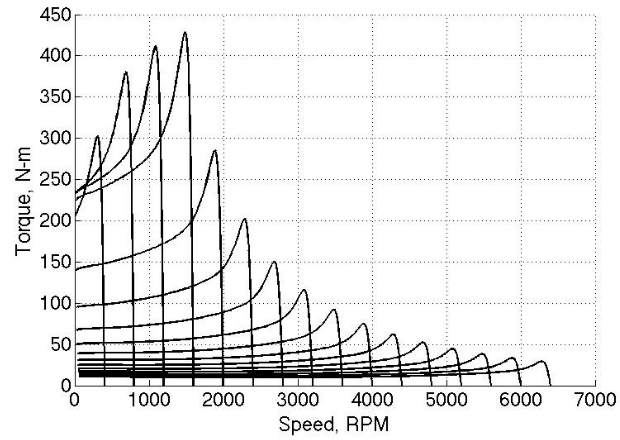

Figure 2 - Illustration of Torque Capability of Induction Machine with Cast Copper Rotor

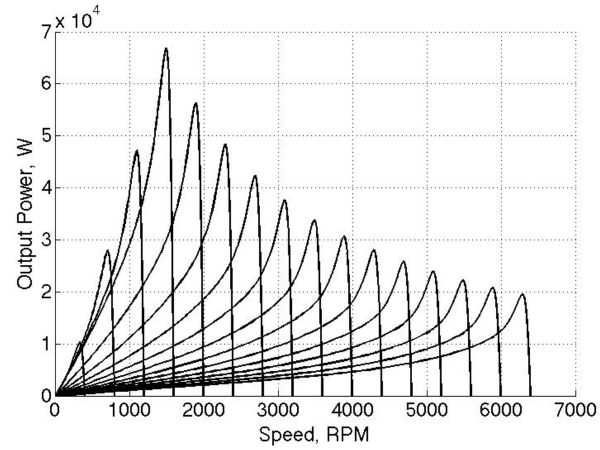

Figure 3 - Power Capability of Induction Machine with Cast Copper Rotor

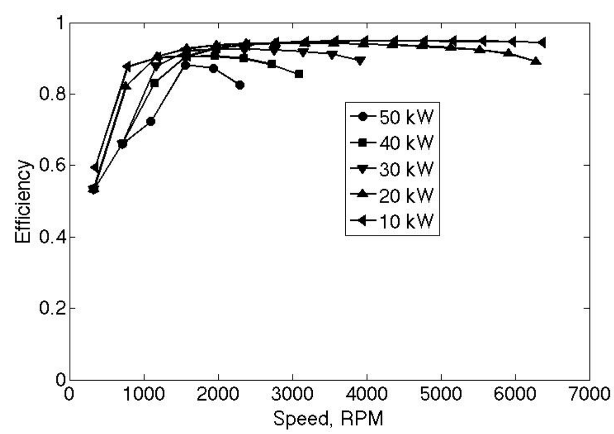

Figure 4 - Efficiency of the Induction Machine with Cast Copper Rotor

Permanent Magnet Machine Efficiency - Losses in the permanent magnet (PM) machine have several components, but the largest components of loss are in the stator copper and in the stator iron. These latter are produced by rotation of the magnetic flux produced by the permanent magnets. The stator iron losses are present whenever the machine is rotating. Because of this ever-present loss mechanism, the effective efficiency of the PM machine is not as high as steady state data might suggest, and at least some hybrid vehicle investigators have determined to use induction machines for this reason [6]. Following our presentation at a recent European conference [7], in this section we examine the efficiency of this type of machine employing a simple model. We start with estimates of loss in the 2004 model Prius motor, made by the team at Oak Ridge National Lab (ORNL) in [5]. At thermally limited torque, with 50 ºC coolant and at 900 RPM, the machine is producing 15,042 watts and has stator conduction loss of 935 watts and core loss of 952 watts. At base speed of 1200 RPM, output power would be 20,056 watts. If we assume core loss is a quadratic function of speed, it would be 1,692 watts at 1200 RPM.

Mechanical power produced by the motor is simply: $P = \Omega T$, where Ω is rotational speed in radians per second and *T* is torque in Newton-meters.

We model loss as $P_D = a\Omega^2 + bT^2$, where a and b are constants related to the core and conduction loss mechanisms. This is, of course, an approximation because core loss is not strictly quadratic in speed and torque is not strictly linear in armature current. We believe that this assumption is close to reality.

Efficiency of the electromagnetic motor mechanism is then:

$$\eta = \frac{P}{P+P_D} = \frac{1}{1+\frac{P_D}{P}} = \frac{1}{1+\frac{a\Omega^2+bT^2}{\Omega T}} = \frac{1}{1+a\frac{\Omega}{T}+b\frac{T}{\Omega}}$$

If we now express rotational speed and torque relative to a base condition:

$$\Omega = \Omega_0\omega \text{ and } T = T_0\tau ,$$

then efficiency can be written in per-unit terms as:

$$\eta = \frac{1}{1+f_\Omega\frac{\omega}{\tau}+f_T\frac{\tau}{\omega}}$$

where the two fractions f_Ω and f_T are the per-unit losses due to core loss and to conduction loss, respectively. For the motor evaluated by ORNL, these are, approximately,

$$f_T = \frac{935}{20056} \approx .047 \qquad f_\Omega = \frac{1692}{20056} \approx .084$$

To evaluate efficiency in a fashion similar to what is expressed in Figure 4, it is necessary to express it in terms of power and speed. This is simply:

$$\eta = \frac{1}{1+f_\Omega\frac{p}{\tau^2}+f_T\frac{\tau^2}{p}}$$

where p is per-unit power. Without considering limits to torque or speed voltage this is shown in Figure 5. While nominal efficiency is relatively high at low speeds, it drops off rapidly for higher speed, particularly at low output power.

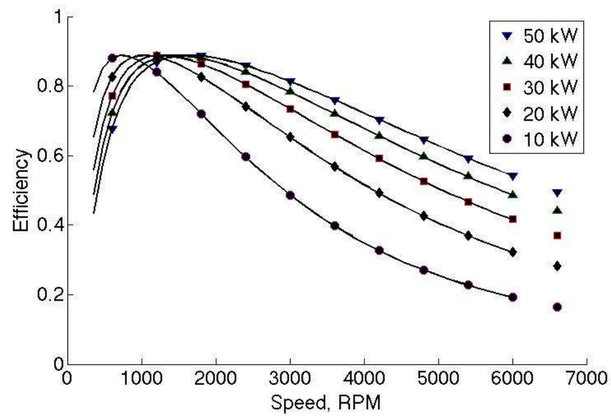

Figure 5 - Estimated efficiency of PM Machine

<u>Effective Efficiency of Traction Motors</u> -To understand the impact of motor losses, including PM drag loss on actual machine operation, we now attempt to evaluate the effective efficiency of a machine with a (hopefully) realistic operating scenario. Recognize that losses in machines come from two sources. First, acceleration force requires current in the windings, so resistive losses occur. Second, rotational speed produces loss from friction, windage and, most important, core loss. In permanent magnet machines there is always flux present so that there will always be rotational losses. Induction motors can be de-excited so that core loss can be 'turned off' when the motor is not producing torque.

We start with a dataset published by the Environmental Protection Agency [8]. Figure 6 shows a distribution of speed measured for a typical automobile for 'all driving'. Figure 7 shows a distribution of acceleration for the same typical automobile. Note that acceleration is both positive and negative. Assuming the drive motor will do regenerative braking, we will treat acceleration as an absolute (positive) value. For the purpose of this analysis, treat both speed and acceleration, which is equivalent to force, as random variables which may or may not be correlated.

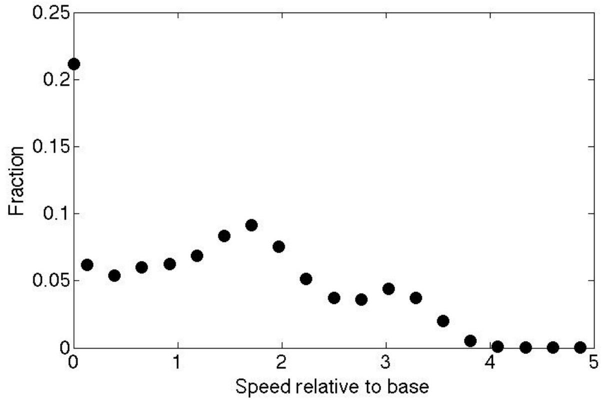

Figure 6 - Speed Distribution

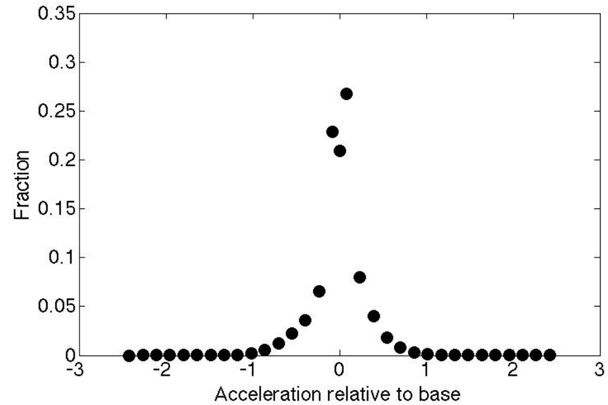

Figure 7 - Acceleration Distribution

Speaking in probabilistic terms, the expected value of mechanical output power is

$$E(P) = E(\Omega F) = E(\Omega)E(F) + \mathrm{COV}(\Omega, F)$$

Where we have used the definition for covariance: $\mathrm{COV}(\Omega, F) = E(\Omega F) - E(\Omega)E(F)$

Expected or average efficiency over some operating range can be estimated as:

$$\eta_E = \frac{1}{1 + \frac{E(P_D)}{E(P)}} = \frac{1}{1 + \frac{aE(\Omega^2) + bE(F^2)}{E(\Omega)E(F) + \mathrm{COV}(\Omega, F)}}$$

Now define a few normalized statistical measures : normalized covariance and variance of speed and force :

$$\sigma_{\Omega F} = \frac{\mathrm{COV}(\Omega, F)}{\sqrt{\mathrm{VAR}(\Omega)\mathrm{VAR}(F)}}$$

$$\sigma_\Omega = \frac{\mathrm{VAR}(\Omega)}{(E(\Omega))^2} \qquad \sigma_F = \frac{\mathrm{VAR}(F)}{(E(F))^2}$$

With these definitions, expected efficiency becomes:

$$\eta_E = \frac{1}{1 + \frac{aE(\Omega^2) + bE(F^2)}{E(\Omega)E(F)\left(1 + \sigma_{\Omega F}\sqrt{\sigma_\Omega \sigma_F}\right)}}$$

Using the normalizations for speed and force developed above, the expected values are simply:

$$E(\Omega^2) = \Omega_0^2 E(\omega^2) \qquad E(F^2) = F_0^2 E(f^2)$$
$$E(\Omega) = \Omega_0 E(\omega) \qquad E(F) = F_0 E(f)$$

And with some manipulation the expected efficiency becomes:

$$\eta_E = \frac{1}{1 + \frac{f_\Omega E(\omega^2) + f_F E(f^2)}{E(\omega)E(f)\left(1 + \sigma_{\Omega F}\sqrt{\sigma_\Omega \sigma_F}\right)}}$$

With this last expression we can translate estimated loss fractions, along with speed and force generation statistics, into an expected operational efficiency. Note that when speed and force generation are held to rated values, the variances go to zero and this expression reduces to the rated efficiency.

To do the comparison described here we must evaluate the normalized fractional losses for the induction machine in the same fashion as was previously done for the permanent magnet machine. These are:

$$f_T = \frac{1787}{20056} \approx .089 \qquad f_\Omega = \frac{173}{20056} \approx .009$$

The expression for effective efficiency has been evaluated for the drive cycle of Figures 6 and 7 for both the permanent magnet machine described by ORNL and for our exemplar induction motor. The results are shown in Figure 8.

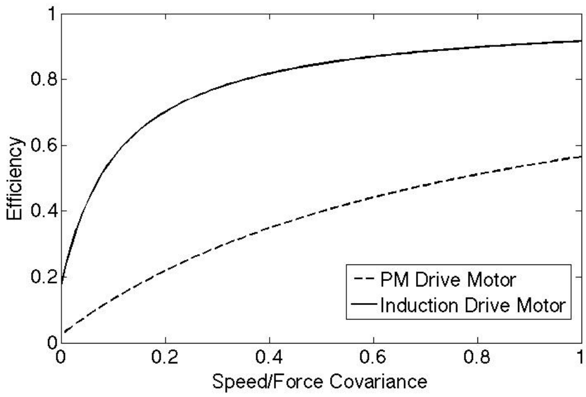

Figure 8 - PM Drive Effective Efficiency

Discussion of Loss Elements - To understand the operational (effective) efficiency, we should review the nature of losses in the two classes of machine. In permanent magnet motors, excitation is provided by the permanent magnets, which are lossless. There is excitation related loss, of course, from eddy currents and hysteresis in the core iron. This loss is roughly quadratic in speed. In the induction motor the excitation is provided by stator currents and so produces some loss. There is also core loss present, of course, and that loss is roughly proportional to the square of terminal voltage. This increases with speed up to the ‘base’ speed. But with appropriate controls the excitation of the induction machine can be set to produce ‘optimal’ losses for any given operating point. It should be pointed out that conduction loss associated with exciting an induction machine is typically quite small; magnetizing inductances of induction machines are large, and so magnetizing current is substantially smaller than load current.

Load loss results from the currents required to produce torque. Load current is inversely proportional to excitation flux and directly proportional to torque. In PM machines, then, torque related losses are proportional to the square of torque. In induction machines the same is true but torque must be produced on the rotor as well, so the induction machine has higher torque related loss.

Figure 8 reflects the common sense notion that the more highly correlated the force required to accelerate a vehicle and the speed of that vehicle the higher will be the effective efficiency. Since there are losses associated with both speed and acceleration but real power is the product of force and speed, when force and speed are not correlated the losses will be higher relative to output power. The induction machine appears to have a higher effective efficiency primarily because it has lower rotational losses.

Figure 8 under-states the effective efficiency advantage of the induction machine for hybrid vehicles because it does not take into account the possibility of de-exciting the induction machine when it is rotating but not producing drive effort, something that is very important in ‘mild’ hybrid vehicles that cruise on engine power only, using the drive motor for acceleration and braking.

Conclusions - The cast copper induction motor presented here is designed with its fundamental requirement that it be able to deliver a peak power of 50 kW over a relatively narrow speed range but with a thermal rating on the order of 25 kW and the capability of producing 20 kW over a very wide speed range. This motor turns out to be nearly the same size as the permanent magnet motor designed for the same purpose. In actual operation as a traction motor the induction machine is more efficient.

In actual vehicle operation, the induction machine has a substantial advantage because it can be de-excited when it is not producing torque, eliminating electrical loss in that condition. The impact of the rotational losses on vehicle efficiency depends, of course on the speed profile of the vehicle. Similarly, the impact of losses in the induction machine depend on required torque production of the machine and, to a lesser extent, on rotational speed. Since those losses are present only when, and to the extent, the induction motor is producing torque, hybrid vehicles are expected to be more efficient when induction machines are used for the drive motor.

TRACTION MOTOR FOR HYBRID ELECTRIC U.S. ARMY TRUCK

THE 140 HP, 12,000 RPM HEMTT-A3 MOTOR - Traction motors for hybrid electric vehicles is an application that has utilized copper die-cast rotor motors to provide higher power density than conventional aluminum rotor motors. This application was selected for a cast copper rotor development in support of a prototype motor project for the latest generation of a U.S. Army severe-duty truck. The truck utilizes four 140-hp electric motors. The competing technology is AC induction motors with aluminum die cast rotors. The 520-V motors are powered by a 400-hp diesel engine, making a hybrid drive system that can move the 35,000-pound vehicles and run a 335-kW generator to operate field hospitals, command centers or airstrips. Copper rotor motor technology offered a number of advantages for this application as explained below.

The innovative hybrid electric drive system is said to decrease truck emissions and increase fuel economy by as much as 40 percent. Aside from several configurations for the military’s 8x8 HEMTT-A3 (Heavy Expanded Mobility Tactical Truck) series, the drive system is also configured for commercial use with refuse vehicles. The expectation is that the new drives will lower life-cycle costs as well as lower interior and exterior noise profiles.

Application Challenges and Solutions - The application needs resulted in a motor that must meet efficiency requirement across a broad range of loads and speeds, yet be small and light enough to meet the space and weight constraints for this vehicle. Two different electric motor designs were developed, one with a cast aluminum rotor cage and one with a die-cast copper rotor cage. Both motors met the efficiency requirements across a broad range of loads and speeds, but the aluminum rotor motor was too large and too heavy to meet the specifications. The die cast copper rotor motor was significantly smaller and lighter than the aluminum rotor design. Figure 9 shows the relative size and weight of the copper rotor motor compared to the aluminum rotor design. The copper die cast rotor motor was 23% lighter and 30% smaller than the aluminum rotor machine.

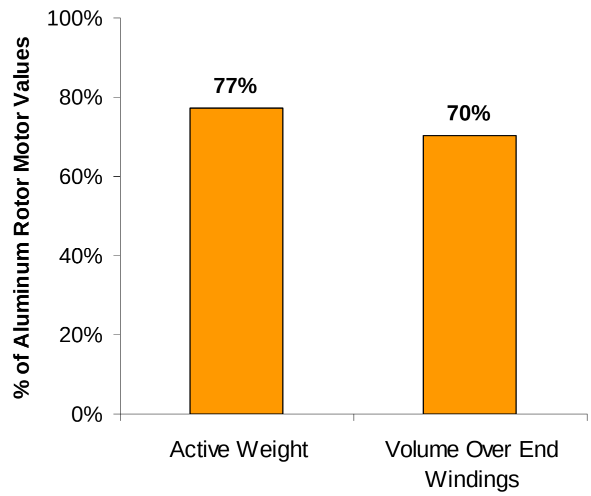

Figure 9 - Relative Weight and Size of the Die-cast Copper Rotor Motor Compared to the Aluminum Rotor Motor

The key to obtaining this size and weight reduction was the ability to redistribute the losses in the copper die cast machine to allow for more effective cooling. For this traction motor application, motor cooling is best obtained by removing heat from the outside of the stator core. Removing heat from the rotor is much more difficult. Taking advantage of the higher conductivity of copper compared to aluminum, the optimized copper motor design moved a substantial portion of the motor losses from the rotor to the stator. Figure 10 shows the loss distribution of the two motor designs. The total rotor loss, consisting of rotor conductor I^2R loss, stray load loss, and friction and windage loss, is reduced from 46% of the motor loss in the aluminum rotor design to 26% of the motor loss in the copper rotor design for rated motor operating conditions. The copper rotor motor loss reduction was obtained by taking full advantage of copper in the rotor to reduce the rotor I^2R loss by more than 50% as shown in Figure 11. This rotor conductor loss reduction is greater than the ratio of copper to aluminum resistivity (about 62% for typical casting alloys) and was obtained by optimizing the rotor design to take full advantage of the cast copper in the rotor slots.

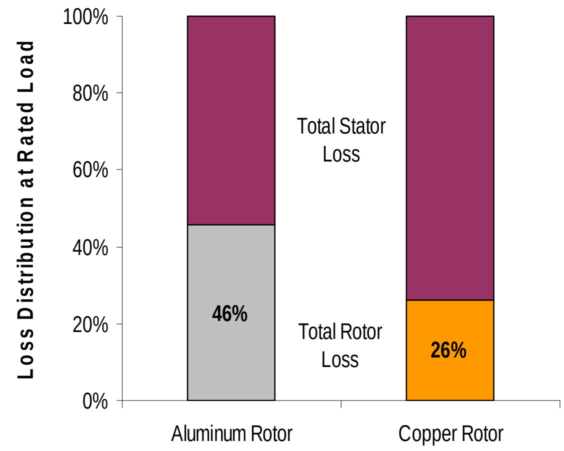

Figure 10 - Loss distribution at full load for the traction motor designs showing a much smaller portion of the motor loss is in the rotor for the copper die cast rotor motor.

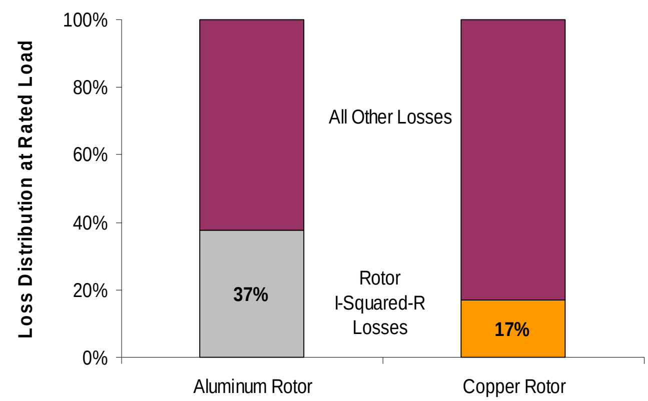

Figure 11 - Loss distribution at rated load showing dramatic reduction in rotor conductor loss with the optimized die cast copper rotor design.

The overall result is a compact, light-weight motor that has a much higher heat transfer across the stator outer wall. Figure 12 compares the global heat transfer capability of the two motors assuming that all of the motor loss drives heat across the stator outer surface. The copper rotor motor had more than a 30% increase in overall heat transfer capability than the equivalent aluminum rotor motor. This increase in effective cooling capability was obtained by redistributing the motor losses from the rotor to the stator so that the resulting heat could be more effectively removed.

Copper rotor motors have historically been manufactured using fabricated copper motor cages. With this type of rotor construction, copper rotor bars are inserted into rotor slots and then brazed to end rings

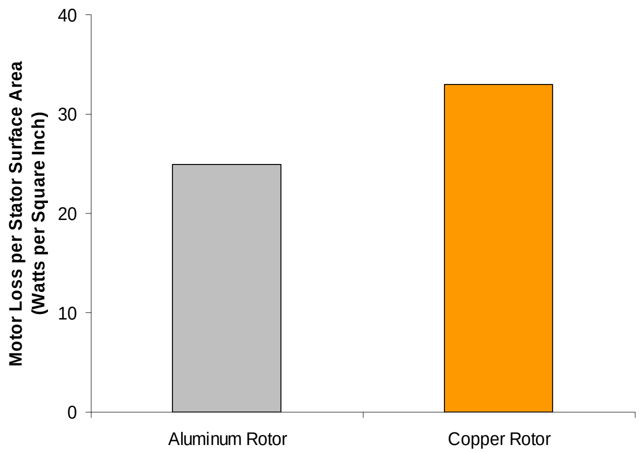

Figure 12 - Total motor loss per stator surface area showing significant improvement with die cast copper rotor design.

as shown in Figure 13. In most cases there is a gap between the rotor lamination stack and the copper end ring where the rotor bars extend beyond the rotor slots before mating with the end ring. For this high speed traction application, the fabricated copper rotor construction would be problematic. The rotor bar extension would contribute to higher friction and windage loss and the interface between the bars and the end ring would result in a stress concentration point. The cast copper rotor, with its end rings tight against the stator core (see Figure 14), provided a more robust mechanical solution than the fabricated copper bar rotor. Due to the higher mechanical strength of copper compared to aluminum, especially at elevated temperature, the die cast copper rotor motor design was more robust than the cast aluminum rotor design for high speed operation as well.

The optimal, high speed, power-dense copper die cast rotor motor met the demanding requirement of this military application. The ability to shift motor losses from the rotor to the stator, where heat removal is much more effective, was the important advantage that the copper die cast rotor technology provided. The added benefit of a more robust rotor mechanical package with the copper die cast rotor was also important to meet the high speed operating requirements of this motor application.

Copper die cast prototype rotors were developed and demonstrated in laboratory test motors and eventually installed in a HEMTT-A3 vehicle for performance testing (Figure 15). The motors have met the requirements of the application in all tests to date.

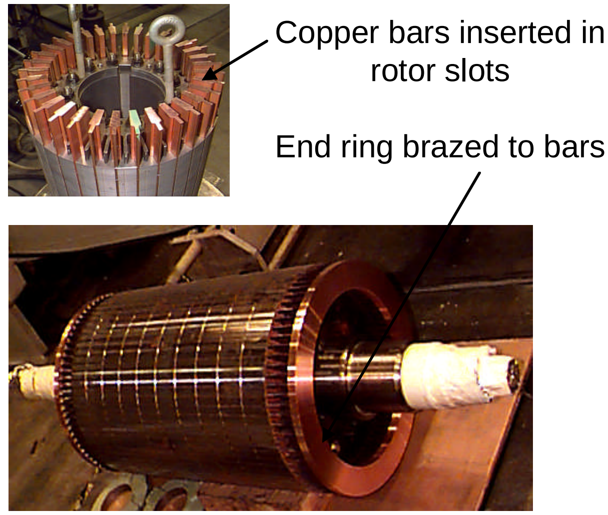

Figure 13 - Fabricated copper bar rotor using traditional copper rotor manufacturing techniques.

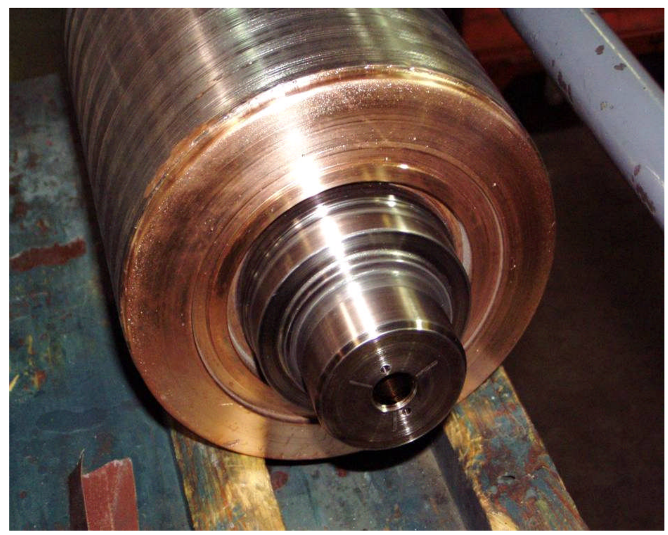

Figure 14 - Copper die cast rotor for the traction motor application.

Figure 15 - HEMTT-A3 vehicle and prototype vehicle with copper motors at AUSA show in Washington, DC in October of 2006.

CONCLUSION

Building a motor around a die-cast copper rotor has proven to be an effective and cost effective design platform for very high efficiency industrial induction motors. With manufacturing know-how in die casting copper with its high melting point well in hand, millions of copper rotor motors are now in use. The copper rotor induction motor appears to be a viable choice for parallel hybrid electric vehicles in terms of overall system efficiency and durability. A motor of this type has been successfully applied in a challenging U.S. Army heavy expanded mobility tactical truck electric drive system. The die-cast copper rotor proved to allow a smaller package with superior heat management and mechanical robustness compared to die-cast aluminum or fabricated copper.

ACKNOWLEDGMENTS

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