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Die-cast Copper Rotors for Smaller High Efficiency Automobile Traction Motors – A Design Study

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ABSTRACT

We consider drive motors for hybrid or electric vehicles. In particular, we explore the relationship between induction machines constructed with die-cast aluminum and copper rotors. Approximate size, weight and performance metrics are deduced for drive motors capable of 60 kW at 1,200 RPM. It is found that the use of a cast copper rotor can result in a drive motor that has an efficiency more than two percent greater than a geometrically similar motor with an aluminum rotor, or that a motor with similar efficiency can be made smaller and lighter than the aluminum rotor motor. A comparative cost analysis for the three induction motors is presented.

INTRODUCTION

The hybrid electric vehicle has shown promise in reducing fuel consumption. The hybrid concept could be a useful tool in national energy strategy to reduce petroleum imports particularly if a portion of the propulsion energy were taken from the electric power grid with a "rechargeable" hybrid. It is important that all components of the drive train be as energy efficient as practicable.

The die-cast copper rotor induction motor has gained a significant foothold in the integral horsepower industrial motor market [1]. Design work in the development of motors meeting or exceeding EPAct and EFF1 efficiency standards has shown that copper rotor motors often allow use of a smaller frame size than the aluminum design and are correspondingly lighter [2-6]. The smaller size and reduced weight obtainable with copper in the rotor could be valuable in automotive traction motors. The objective of this study was to explore the feasibility of the induction motor to automotive traction, particularly in the hybrid vehicle We present, first, a 60 kW traction motor designed with a cast aluminum rotor. We then evaluate the same design with copper substituted for the aluminum. Finally we design a machine with a copper rotor that approximates the performance of the original aluminum rotor machine do show a reduced size and weight attainable with cast copper rotors.

The term "die-cast" is used in the title of this paper to make the point that the subject copper rotor is in fact a mass produced component using high pressure die casting to form the rotor squirrel cage structure as is conventionally done with the aluminum rotor. Fabrication of copper rotors is standard practice for very large motors but is not cost effective for large scale production. Because of the high melting temperature of copper compared to that of aluminum, manufacture of the copper rotor by die casting had been regarded as a barrier to production because of the rapid deterioration of the dies. Work by the Copper Development Association in the past few years has demonstrated that nickel-base alloy die inserts operated at about 1225° F very significantly extend tool life [7, 8]. Practical high temperature copper die casting plants using this technology are now in operation. FAVI, SA in France has also applied their proprietary technology to production of thousands of copper rotors for European motor manufacturers [9].

TRACTION MOTORS FOR VEHICLES

Both total mass and efficiency are important in hybrid and electric vehicle propulsion motors. Much attention has been placed on permanent magnet motors for this purpose. The use of permanent magnets generally permits motors to be light in weight and quite efficient.

However, the fact that the permanent magnet excitation is always present forces the need for some compromises in the design of traction motors. First, traction motors must operate over a wide speed range, so that there is a tradeoff between providing enough torque at low speed and controlling terminal voltage at high speed. This is usually accomplished by making the motor highly salient and using a relatively weak permanent magnet [10]. Negatively salient motors employ 'buried' magnets located in slots below the rotor surface that introduce magnetic reluctance that reduces inductance in the 'direct' axis of the motor. The 'quadrature' axis has higher inductance. The resulting asymmetry in inductance is called 'saliency' and is useful in producing torque at the expense of relatively large stator currents. The compromises that must be made to permanent magnet machines to permit a wide operating speed range make the motor larger and less efficient.

The second issue is that permanent magnet motors have some loss whenever the motor is turning [11]. Because of these issues, we are considering the use of induction machines for traction drive motors. We estimate that the induction machines presented here are about the same physical size and mass as would be a buried magnet permanent magnet motor and would have comparable efficiency. Depending on drive cycle, the induction machines would have an overall energy efficiency higher than the permanent magnet machine because of the idling drag loss in the permanent magnet machine.

BASELINE MOTOR (CASE 1)

Selected for this study is a motor rated at 60 kW at 1,200 RPM. While this machine is not intended for any particular drive application, it is thought to be representative of the size and speed range required of a drive motor for either a series electric or hybrid electric vehicle. An induction machine using a conventional squirrel cage, die-cast aluminum rotor was designed, essentially from a clean sheet of paper. It is a six pole machine so that synchronous frequency at 1200 RPM is 60 Hz. Basic dimensions of this motor are:

Table 1: Basic Motor Dimensions

Rotor Radius	3.500"
Active Length	7.000"
Slot Depth	1.500"
Number of Stator Slots	54
Number of Rotor Slots	39

The stator winding for the machine is a conventional winding, with three slots per pole per phase, short pitched by one slot. It uses 21 strands of AWG 18 wire, four turns per coil and thus a total of 72 turns per phase. Base voltage is 250V, RMS. If connected in delta, this would require a DC bus voltage of about 400 V.

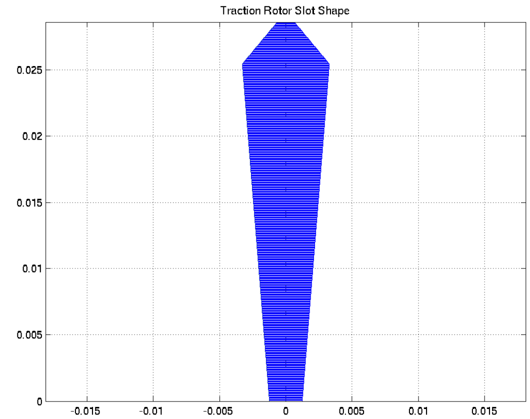


Figure 1: Rotor Bar Shape

The rotor is assumed to be a standard squirrel cage with bars shaped as shown in Figure 1. Since this is to be a traction motor driven by an inverter, starting performance is not an issue and the bar is sized to put as much conductor as is practicable in the rotor.

MODIFICATIONS TO THE MOTOR

Two modifications to the machine were considered:

SUBSTIUTION OF COPPER (Case 2)

The first and most obvious modification was a simple substitution of copper for the aluminum of the squirrel cage. No other modifications were made to the basic motor design, so the size of the motor is unchanged, but of course it is a bit heavier due to the higher mass density of the copper.

REDUCED SIZE WITH CAST COPPER CAGE (Case 3)

The cast copper rotor makes the machine more efficient but a bit heavier. It also reduces the heat dissipation in the rotor. It is possible to convert the same power in a smaller package, at some penalty to motor efficiency. A smaller machine was designed to produce the same efficiency as the aluminum rotor machine. This motor is both smaller in diameter and length and it turns out to be a bit lighter as well. The major dimensional changes are:

Table 2: Changed Dimensions of Smaller Motor

Rotor Radius	3.25"
Active Length	6.5"

To keep the designs properly comparable, terminal voltage was reduced for the reduced size machine so that air-gap and steel flux densities are nearly the same. This meant that terminal voltage is proportional to rotor area. In this case, baseline phase voltage is 215 V, RMS.

BASIC PERFORMANCE METRICS

The basic performance metrics and gross dimensions of the three machines are shown in Table 3. These were calculated using design evaluation code that has been calibrated against production induction motors and appears to be accurate. Conventional silicon iron laminations are assumed in computation of core loss. The copper is assumed to have a conductivity of 100% of IACS corrected to 95C. The aluminum conductor is assumed to have a base conductivity of 50% of IACS and is also corrected to 95C. This temperature is assumed to be consistent with vehicle cooling systems.

Table 3: Basic Performance of Three Machines

	Al Cage (Case 1)	Cu Cage (Case 2)	Reduced Size Cu (Case 3)
Overall Diameter	11.730”	11.730”	11.570”
Overall Length	10.665”	10.665”	9.653”
Active Material Mass	92.35 kg	101.12 kg	86.1 kg
Efficiency at base point	91.6 %	93.8%	91.5%
Power Factor at base point	80.0%	79.8%	77.4%

Simple substitution of copper increases efficiency of the motor by 2.2%, implying a reduction of losses by about 26%. The reduced size machine is about as efficient as the baseline machine but is smaller and less massive. Not taken into account in these calculations is the fact that the copper rotor will run substantially cooler than the aluminum rotor. We estimate that the ‘efficiency coefficient of temperature’ is about .0124% per degree Kelvin. This means that if the aluminum rotor runs 20C hotter than the copper rotor, our results understate the efficiency advantage of the copper rotor by about 1/4 of one percent.

A comparison of torque speed curves for the three motor design cases is shown in Figure 2. As expected, the copper torque/speed curve is steeper in the operating region, reaches maximum torque at a lower slip and has a lower locked-rotor torque. The reduced size motor has a lower torque-speed curve, again as expected.

Operation of a motor at its rated point is not, of course, the only important metric, since all traction motors will be operated at different loads and speeds. For this reason we consider how the different motors operate over a range of loads.

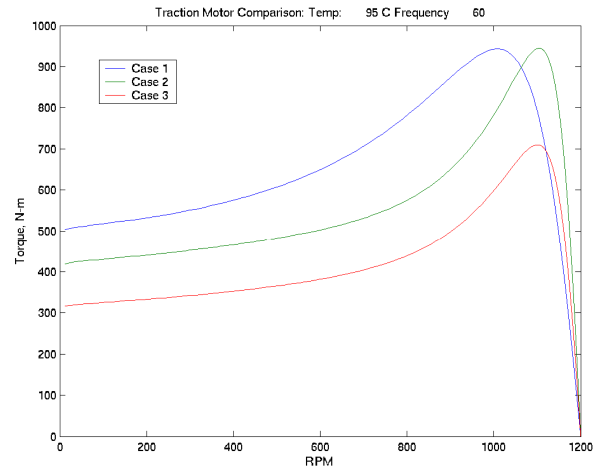


Figure 2: Comparison of Torque-Speed Curves at 60 Hz:

Figure 3 shows efficiency of the three motors over a range of loads, from10 kW to 70 kW, assuming a supply frequency of 60 Hz. This is representative of what the machines would produce at 1,200 RPM. The copper machine cast in the same slots as the aluminum machine has consistently higher efficiency. The reduced size copper machine has efficiency almost identical to that of the aluminum machine over the whole range of operation.

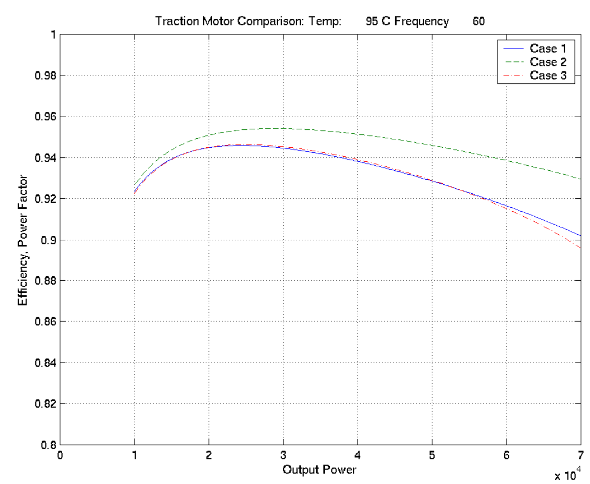


Figure 3: Comparison of operating efficiencies at 60 Hz

DIFFERENT FREQUENCIES

We considered operation at frequencies both below and above the ‘base’ frequency. Operation at 30 Hz, or roughly half of base speed, is shown in Figures 4 and 5. In this operating condition the machine voltage should be reduced (we use a scheme that is nearly 'volts per Hz'). For the full size machines voltage assumed is 130 V, RMS and for the reduced size machine it was 112.5 V, RMS.

For operation at reduced frequency and voltage, the machine can produce rated torque, as shown in Figure 4, but has a power capability that is also smaller than at base conditions.

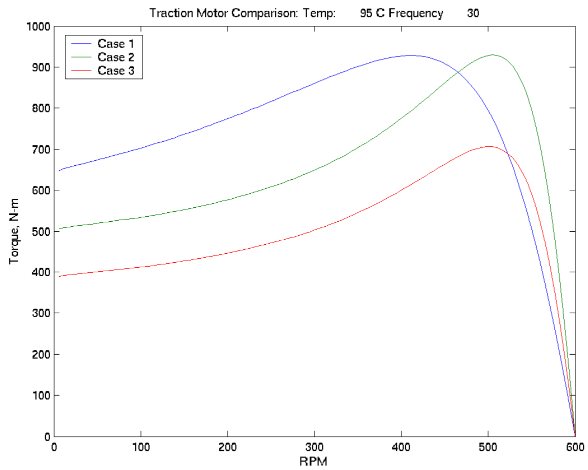


Figure 4: Comparison of Torque Speed Curves at 30 Hz.

For reduced frequency operation the reduced size machine efficiency nearly tracks that of the aluminum machine. At high loads, as the machine approaches its breakdown torque, slip increases and efficiency falls a bit faster. The copper machine in baseline slots has consistently higher efficiency.

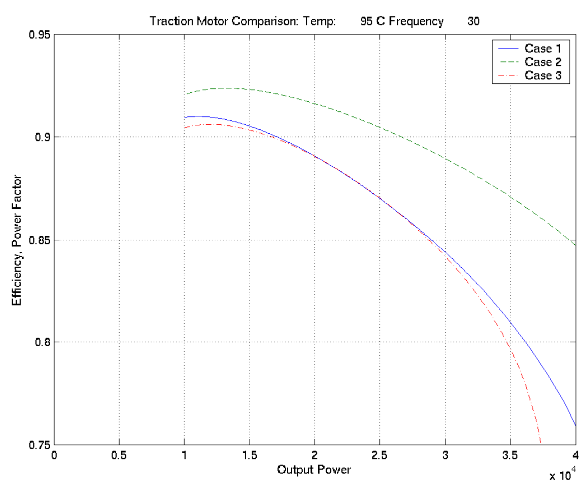


Figure 5: Efficiency Comparison at 30 Hz

At frequencies higher than baseline, where terminal voltage is held fixed, the motor can not make as much torque and so power output is limited. This can be seen in both the torque-speed comparison (Figure 6) and the efficiency comparison (Figure 7), where the reduced size machine torque capability falls off faster with supply frequency than that of the full sized machines.

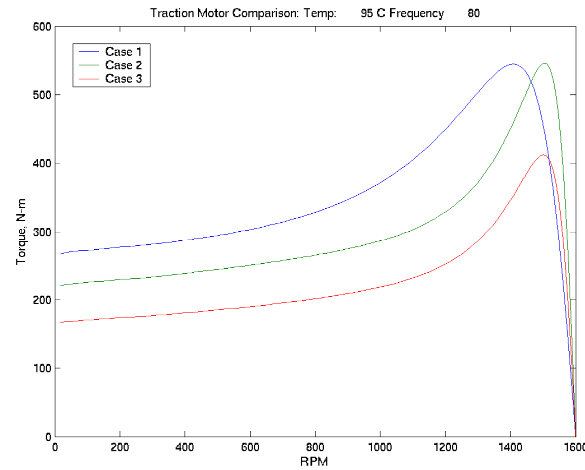


Figure 6: Comparison of Torque at 80 Hz

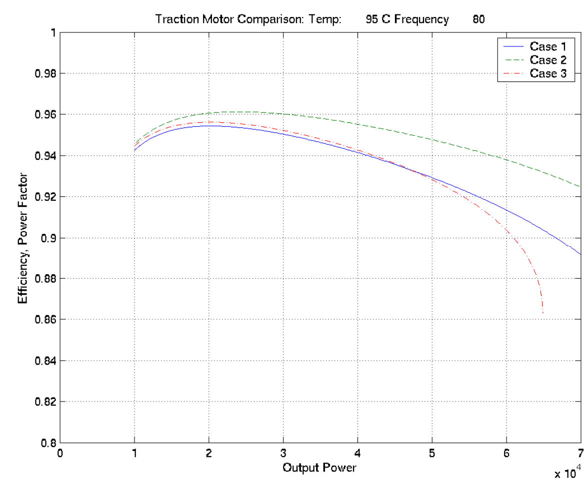


Figure 7: Comparison of Efficiency at 80 Hz

Capability

For low speed operation the motor is torque limited because flux is limited by the magnetic circuit and current is limited by heating. Voltage, being proportional to flux times frequency, rises with speed. The 'base' frequency is the point at which the power supply voltage matches terminal voltage (flux times frequency). Above that torque capability falls as, roughly, frequency squared. This is shown in Figure 8, which shows torque/speed curves for several frequencies, for the aluminum rotor machine. Superimposed, in a dashed curve, is the expected capability: constant torque below base speed, constant frequency above. Figure 9 shows the same for the machine built with a copper rotor die cast into the same laminations as the aluminum rotor.

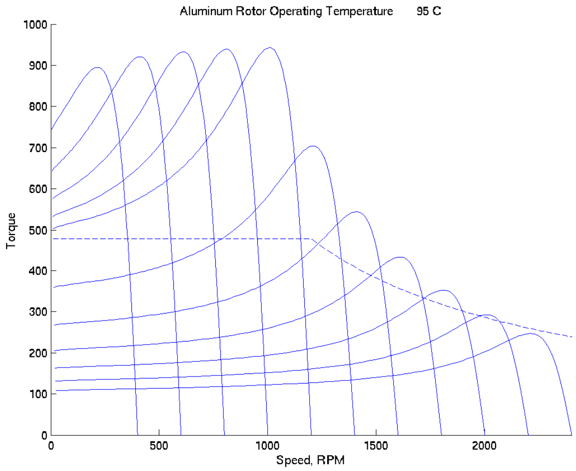


Figure 8: Capability of the Aluminum Rotor Machine

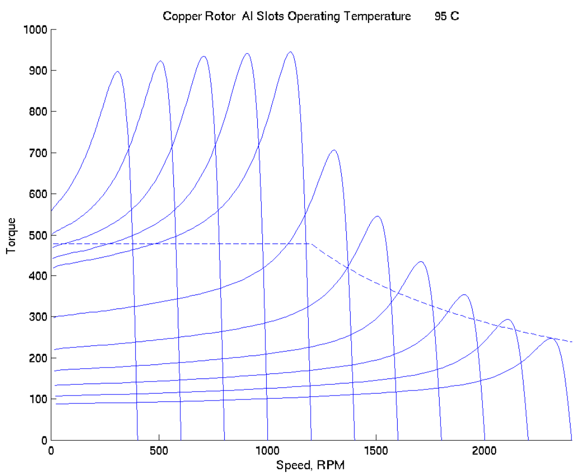
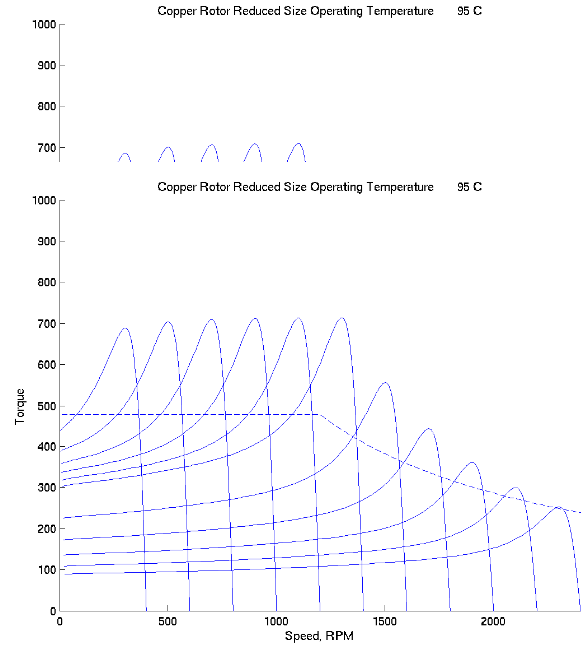


Figure 9: Capability of Copper Rotor Machine in Aluminum Slots

Note that the two machines have nearly the same capability; the machine with copper in the same slots has a slightly higher power capability because the slip is smaller for each curve.

The reduced size machine does not have the same capability and would have a reduced 'constant power' range of speed, as is shown in Figure 10. A slight increase in base frequency, from 60 to 70 Hz, which would constitute an increase in power supply voltage (to the same value as for the aluminum rotor machine) increases the constant power range to nearly 2400 RPM (Figure 11).



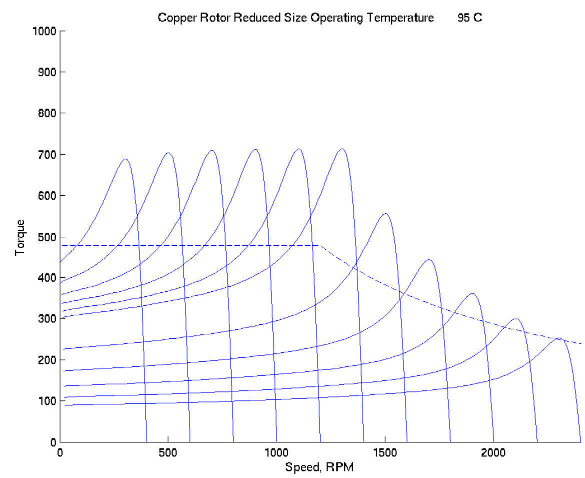


Figure 11: Capability with Increased Base Frequency

Cost Consideration

Copper costs more than aluminum, so that the copper rotor machine may be more expensive than an aluminum rotor machine. Offsetting this is the reduction in losses and/or volume and mass of the machine offered by copper in the rotor. An analysis of the manufactured cost of the machine is reflected in Table 4. This cost analysis is based on assumed prices per kilogram of magnetic steel, wire for the stator winding and rotor conductor (aluminum or copper) and some assumed costs for other elements of the machine such as shaft and housing, etc. The cost of the copper rotor is higher than that of the aluminum rotor, but the machine is quite a bit more efficient. The reduced size machine has a cost that is essentially indistinguishable from the aluminum rotor machine, and this copper rotor machine is smaller and lighter.

Table 4: Cost Analysis

	Aluminum Cage (Case 1)	Copper Cage (Case 2)	Reduced Size Copper (Case 3)
Iron Laminations (kg)	64.6	64.6	53.4
Required Steel (kg)	82	82	67.8
Steel Burden	$65	$65	$55
Lamination Steel Cost	$227.81	$227.81	$189.65
Stator Winding (kg)	23.8	23.8	22.2
Stator Winding Cost	$107.42	$107.42	$100.43
Rotor Conductor (kg)	3.8	12.5	10.5
Rotor Conductor Price ($/kg)	$2.86	$7.06	$7.06
Rotor Conductor Cost	$11.84	$91.55	$77.09
Shaft & Housing	$53	$53	$48
Assembly & Test	$45	$45	$40
Total Cost	$500.07	$579.78	$504.18
Total Mass	92.35 kg	101.12 kg	86.1 kg

CONCLUSIONS

There may be good reasons for using induction machines in electric and hybrid drives. They appear to have power densities and efficiencies comparable to those of permanent magnet machines and, when not excited, they have no electromagnetic losses.

Induction motors made with cast copper rotors can, if properly designed, have size and weight and/or efficiency advantages over similarly rated aluminum machines.

ACKNOWLEDGMENTS

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