Traction Motor Design Considerations

A concept paper in response to the FOA #DE-FOA-0000472 entitled ‘Rare Earth Alternatives in Critical Technologies for Energy (REACT)

Abstract :

In vehicle drives, induction machines properly designed for the application can have efficiencies substantially higher than those of permanent magnet machines, even if the single point efficiency of the induction machine is lower than the single point efficiency of the permanent magnet machine. The objective of the proposed research is to find out how to design induction motors for drive applications by considering, in detail, the actual drive cycle of the vehicle.

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1 Introduction

This is a concept paper in response to the FOA entitled 'Rare Earth Alternatives in Critical Technologies for Energy (REACT)'. Some of the technical discussion is based on work that has been reported in a conference publication[1]. This discussion is not so much about induction motors as it is about motor design. The hypothesis here is twofold: first, that induction motors hold the promise of being as efficient as, or even more efficient than permanent magnet motors in drive applications; second, that design for a specific application will make a superior motor. We argue here that permanent magnets are not required for high efficiency vehicle propulsion motors and have demonstrated, analytically, that induction machines can be designed to have superior performance to permanent magnet machines as propulsion motors for hybrid electric vehicles.

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. The requirement for performance over a relatively wide speed range can force some compromises in permanent magnet motor design, however. Voltage control considerations require that the permanent magnet flux be restricted, and then to produce high torque at low speeds, motors are often made highly salient. The 'straw man' machine in this case is the drive motor from a Toyota Prius, analyzed by a team from Oak Ridge National Labs. The Prius motor, like other machines intended for automotive drive applications, is salient, with the permanent magnets placed in slots in the rotor, oriented in the 'direct' axis which has a reactance substantially less than that of the 'quadrature' axis. This difference in reactance (called saliency) is used to produce torque.

1.1 Baseline Requirement:

The permanent magnet 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[1] In the steady state, estimates of power capability range from about 12 kW to 22 kW, depending on coolant temperature.[2] 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%.

2. Induction Motor:

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[1] J.L. Kirtley Jr., R. F. Schiferl, D.T. Peters, E.F. Brush, Jr.: "The Case for Induction Motors with Die-cast Copper Rotors for High Efficiency Traction Motors", **Society of Automotive Engineers World Congress**, April 22, 2009, Detroit.

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. This is the result of a design choice : the aluminum rotor motor could have been made physically smaller but with lower efficiency. Once the weight of a machine casing is added, this machine would be heavier as well.

Envelope numbers for the permanent magnet machine are included in the table and an estimate of efficiency, based on measurements contained in [2].

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 of Active Material	40.7 kg	40.6 kg	
Peak Efficiency	91 %	91%	87%
Power Factor	73%	68%	

2.1 Induction Motor Performance

Torque capability of the induction machine with the copper rotor is shown in Figure 1, and power capability (just speed times torque) is shown in Figure 2, to illustrate that the motor does have the peak capability required.

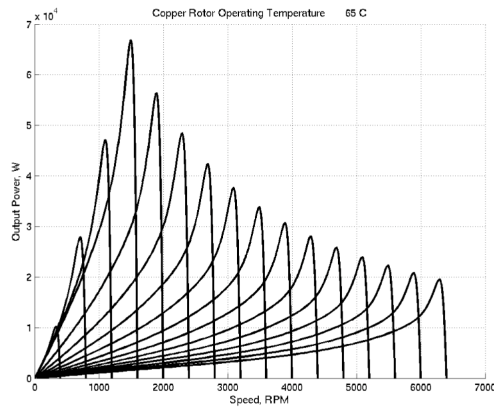

Figure 1: Illustration of Torque Capability of Induction Machine with Cast Copper Rotor

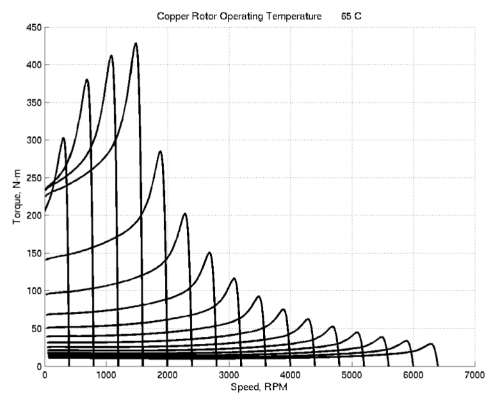

Figure 2: Power Capability of Induction Machine with Cast Copper Rotor

2.2 Induction Motor Efficiency

Efficiency of the cast copper induction machine is shown in Figure 3. 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.

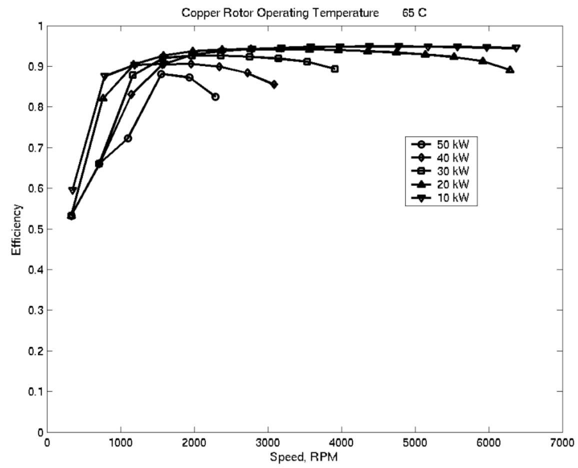

Figure 3 Induction Motor Efficiency

2.3 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. Those 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[3]. 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 [2]. At thermally limited torque, with 50 C 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 20056 watts. If we assume core loss is a quadratic function of speed, it would be 1692 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: $\Omega = \Omega_0 \omega$ 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 4. While nominal efficiency is relatively high at low speeds, it drops off rapidly for higher speed, particularly at low output power.

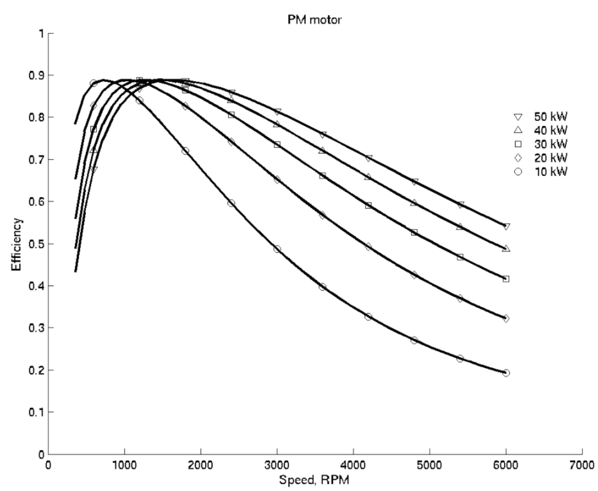

Figure 4: Estimated Efficiency of PM Machine

3 Effective Efficiency of Traction Motors

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.

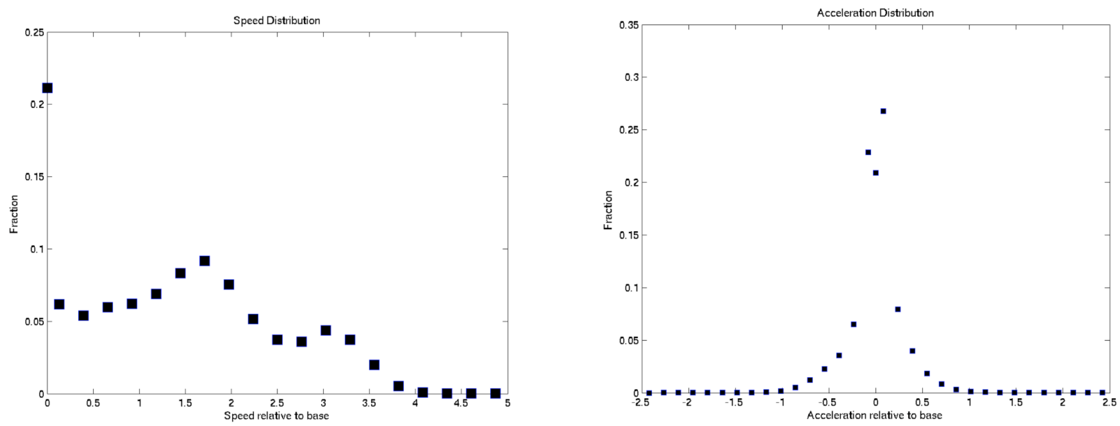

Figure 5: Drive Cycle Speed and Acceleration

We start with a dataset published by the Environmental Protection Agency[4]. Figure 5 shows a distribution of speed and acceleration measured for a typical automobile for ‘all driving’. 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.

Speaking in probabalistic 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 :

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

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

With these definitions, expected efficiency becomes:

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

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

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

And with some manipulation the expected efficiency becomes:

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

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 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 Figure 5 for both the permanent magnet machine described by ORNL and for our exemplar induction motor. The results are shown in Figure 6.

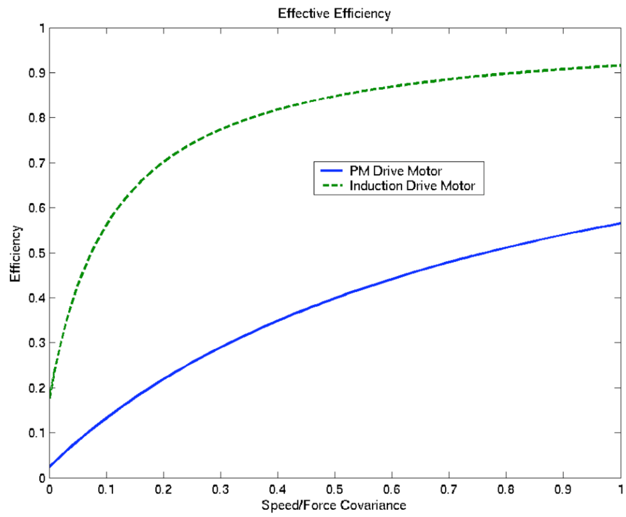

Figure 6: Overall Drive Cycle Efficiencies

4 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 6 reflects the common sense notion that the more highly correllated 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 correllated 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. In a very real sense, Figure 8 understates the effective efficiency advantage of the induction machine 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.

5 Sensitivity

Out of concern that the data we had for the Prius motor may have been incorrect (leading to pessimistic predictions for efficiency, this analysis was reworked assuming lower loss coefficients for the permanent magnet motor. The new coefficients assumed were :

$$f_T = \frac{935}{20056} \approx .024 \qquad f_\Omega = \frac{1692}{20056} \approx .042$$

Efficiency of the permanent magnet motor under these assumptions is shown in Figure 7. Maximum efficiency of the motor is now calculated to be about 94%. Using the same assumptions, drive cycle efficiency was recalculated and the results are shown in Figure 8.

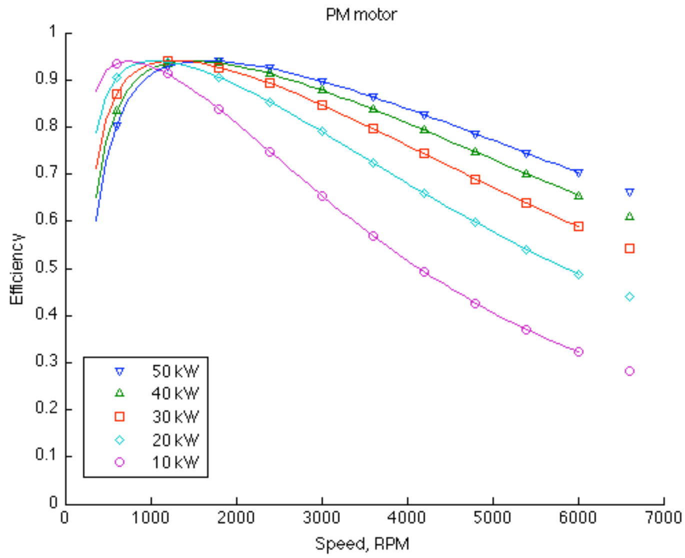

Figure 7: PM Motor Efficiency with revised assumptions

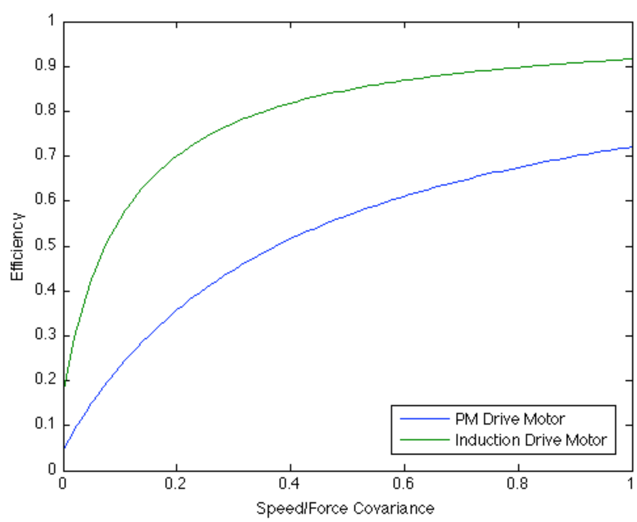

Figure 8: Drive Cycle Comparison with Revised PM Efficiency Assumptions

6 Conclusions

The induction motor presented here, designed with the fundamental requirement that it be able to deliver a peak power of 50 kW over a relatively narrow speed range, turns out to be nearly the same size as the permanent magnet motor designed for the same purpose. In application with a typical driving cycle, the induction machine turns out to be more efficient. This conclusion is robust, even if the permanent magneti machine is more efficient at its peak efficiency operating point. Figure 8 shows that the effective efficiency of both machines in actual operation to be much less than the nominal efficiency of each of the motors at their rated operating point. In actual vehicle operation, the induction machine has a substantial advantage because it can be de-excited when it is not producing torque, eliminating idling electrical loss. 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.

The induction motor design and comparison with the permanent magnet motor were just a quick study done to investigate the possibilities of using induction machines in hybrid car drives. No attempt was made to determine possible ranges of the speed/force covariance. If invited, we will write a proposal to do a careful investigation of vehicle drive systems, taking into account a wider range of drive cycles, attempting to determine if there actually is a value or range of values for speed/force covariance, establish a carefully thought out objective function (weight/efficiency tradeoff) for the drive motor and then doing a more rigorous optimization of the induction machine. We think we can do substantially better than the machines designed for this quick study.

References

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