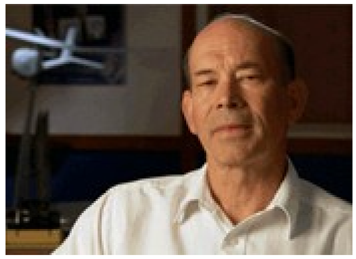

Induction Versus DC Brushless Motors

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published Tuesday, January 9th, 2007

Wally Rippel is a long-time proponent of electric vehicles. Prior to joining Tesla Motors, he was an engineer at AeroVironment, where he helped develop the EV1 for General Motors and was featured in the documentary movie, Who Killed the Electric Car? Wally has also worked for the Jet Propulsion Laboratory on electric vehicle battery research, among other projects. In 1968, as a Caltech undergraduate student, he built an electric car (a converted 1958 Volkswagen microbus) and won the Great Transcontinental Electric Car Race against MIT.

One Size Does Not Fit All

In that odious world of gas powered vehicles, engines are not all alike. There are flat-heads, Hemis, straight, opposed, and V configurations. And on and on. One would have thought that, years ago, someone would have figured out which was best. That would have ended all the choices and thereafter only the one best engine type would be in production. Not so. There is no one best engine type, rather there are different types of engines to suit personal requirements, such as price and performance. This is also true for electric vehicle drives.

Back when I had hair on my head and carried a slide rule, there were lead acid batteries, DC brush motors, and contactor controllers. Today, none of these remain (including my hair). Lead has been replaced by lithium and DC by either DC brushless or induction. Contactors, meanwhile, have given way to modulating inverters. So, will each of these elements also become obsolete in the near future or is it possible that some "stability" may be at hand? Without a good crystal ball, it is hard to predict the future. My guess, however, is that we will see both induction and brushless machines "duke it out" for many years to come. Each will have its loyal proponents and religious detractors.

A Closer Look

So what are these two technologies? How do they work? What differentiates them? And what do they have in common? Let's start with DC brushless drives.

With brushless machines, the rotor includes two or more permanent magnets that generate a DC magnetic field (as seen from the vantage point of the rotor). In turn, this magnetic field enters the stator core (a core made up of thin, stacked laminations) and interacts with currents flowing within the windings to produce a torque interaction between the rotor and stator. As the rotor rotates, it is necessary that the magnitude and polarity of the stator currents be continuously varied – and in just the right way - such that the torque remains constant and the conversion of electrical to mechanical energy is optimally efficient. The device that provides this current control is called an inverter. Without it, brushless motors are useless motors.

Let's move on to induction motor drives. A forerunner of the 3-phase induction motor was invented by Nikola Tesla sometime before 1889. Curiously, the stators for the 3-phase induction motor and the DC brushless motor are virtually identical. Both have three sets of "distributed windings" that are inserted within the stator core. The essential difference between the two machines is with the rotor.

Unlike the DC brushless rotor, the induction rotor has no magnets – just stacked steel laminations with buried peripheral conductors that form a "shorted structure." Currents flowing in the stator windings produce a rotating magnetic field that enters the rotor. In turn, the frequency of this magnetic field as "seen" by the rotor is equal to the difference between the applied electrical frequency and the rotational "frequency" of the rotor itself. Accordingly, an induced voltage exists across the shorted structure that is proportionate to this speed difference between the rotor and electrical frequency. In response to this voltage, currents are produced within the rotor conductors that are approximately proportionate to the voltage, hence the speed difference. Finally, these currents interact with the original magnetic field to produce forces – a component of which is the desired rotor torque.

When a 3-phase induction motor is connected to utility type 3-phase power, torque is produced at the outset; the motor has the ability to start under load. No inverter is needed. (Were an inverter needed, Tesla's invention would have been useless until sometime in the 1960s.) The fact that induction motors are directly compatible with conventional utility power is the main reason for their success. In contrast, a brushless DC motor produces no starting torque when directly connected to fixed frequency utility power. They really need the aid of an inverter whose "phase" is maintained in step with the angular position of the rotor.

While 3-phase induction motors have great utility, they also have some severe limitations. They cannot operate from DC; AC is a must. Shaft speed is proportionate to line frequency. Hence, when used with utility power, they are constant speed machines. Finally, when operated from utility power, they have limited starting torque and somewhat limited running peak torque capabilities, when compared to DC type machines.

Add an inverter (without any feedback control) and it becomes possible to power an induction machine from a battery or other DC source; variable speed also becomes possible simply by adjusting the inverter frequency. Still, torque performance is low compared with DC machines. Add some feedback loops such that the inverter produces the exact frequency that the motor "desires," and the induction motor is now capable of competing with DC and DC brushless for vehicle applications.

Brushless or Induction?

Back in the 1990s all of the electric vehicles except one were powered by DC brushless drives. Today, all the hybrids are powered by DC brushless drives, with no exceptions. The only notable uses of induction drives have been the General Motors EV-1; the AC Propulsion vehicles, including the tzero; and the Tesla Roadster.

Both DC brushless and induction drives use motors having similar stators. Both drives use 3-phase modulating inverters. The only differences are the rotors and the inverter controls. And with digital controllers, the only control differences are with control code. (DC brushless drives require an absolute position sensor, while induction drives require only a speed sensor; these differences are relatively small.)

One of the main differences is that much less rotor heat is generated with the DC brushless drive. Rotor cooling is easier and peak point efficiency is generally higher for this drive. The DC brushless drive can also operate at unity power factor, whereas the best power factor for the induction drive is about 85 percent. This means that the peak point energy efficiency for a DC brushless drive will typically be a few percentage points higher than for an induction drive.

In an ideal brushless drive, the strength of the magnetic field produced by the permanent magnets would be adjustable. When maximum torque is required, especially at low speeds, the magnetic field strength (B) should be maximum – so that inverter and motor currents are maintained at their lowest possible values. This minimizes the $I^2 R$ (current^2 resistance) losses and thereby optimizes efficiency. Likewise, when torque levels are low, the B field should be reduced such that eddy and hysteresis losses due to B are also reduced. Ideally, B should be adjusted such that the sum of the eddy, hysteresis, and I^2 losses is minimized. Unfortunately, there is no easy way of changing B with permanent magnets.

In contrast, induction machines have no magnets and B fields are "adjustable," since B is proportionate to V/f (voltage to frequency). This means that at light loads the inverter can reduce voltage such that magnetic losses are reduced and efficiency is maximized. Thus, the induction machine when operated with a smart inverter has an advantage over a DC brushless machine – magnetic and conduction losses can be traded such that efficiency is optimized. This advantage becomes increasingly important as performance is increased. With DC brushless, as machine size grows, the magnetic losses increase proportionately and part load efficiency drops. With induction, as machine size grows, losses do not necessarily grow. Thus, induction drives may be the favored approach where high-performance is desired; peak efficiency will be a little less than with DC brushless, but average efficiency may actually be better.

Permanent magnets are expensive – something like $50 per kilogram. Permanent magnet (PM) rotors are also difficult to handle due to very large forces that come into play when anything ferromagnetic gets close to them. This means that induction motors will likely retain a cost advantage over PM machines. Also, due to the field weakening capabilities of induction machines, inverter ratings and costs appear to be lower, especially for high performance drives. Since spinning induction machines produce little or no voltage when de-excited, they are easier to protect.
I almost forgot: Induction machines are more difficult to control. The control laws are more complex and difficult to understand. Achieving stability over the entire torque-speed range and over temperature is more difficult with induction than with DC brushless. This means added development costs, but likely little or no recurring costs.

Still No Winner

My conclusion is that DC brushless drives will likely continue to dominate in the hybrid and coming plug-in hybrid markets, and that induction drives will likely maintain dominance for the high-performance pure electrics. The question is what will happen as hybrids become more electrically intensive and as their performance levels increase? The fact that so much of the hardware is common for both drives could mean that we will see induction and DC brushless live and work side by side during the coming golden era of hybrid and electric vehicles.