Electric Vehicle Motors Go Head to Head

The case for either the permanent magnet or the induction motor design is unclear, so how do hybrid vehicle OEMs decide which is best?

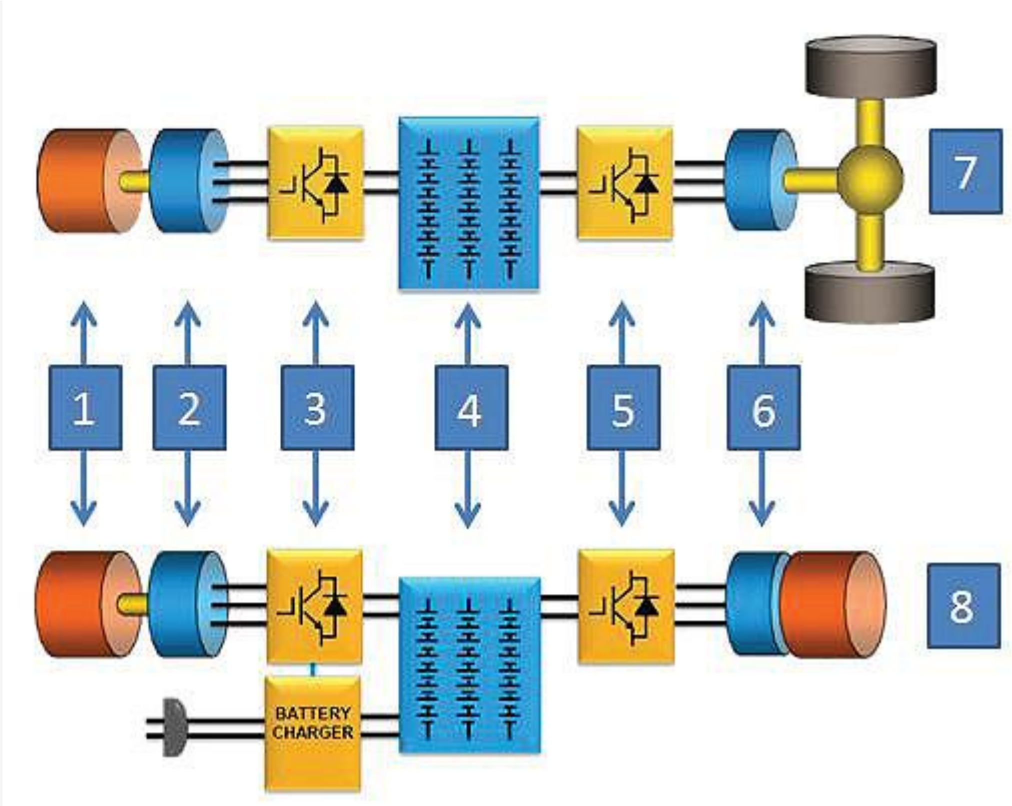
Jay Schultz, Industry Market Manager
and Steve Huard, PhD, Principal Engineer, Parker Hannifin Corporation

Over the last several years, higher fuel prices, consumer demands for better fuel economy, and government regulations requiring lower greenhouse gasses have pushed OEMs to increase the efficiency of their vehicles. In one approach, OEMs are developing hybrid electric vehicles (HEV) on a number of different platforms including cars, trucks, work boats and construction equipment.

In implementing a hybrid program, most vehicle OEMs will choose between either an induction motor (IM) or a permanent magnet AC (PMAC) motor. A recent study used finite element analysis (FEA) software to help determine the best choice.

A Closer Look at Hybrid Electric Vehicles
The Toyota Prius provides a good example of a hybrid electric passenger car, with similar adaptations of the technology now implemented in many kinds of other vehicles. The Prius uses electric technology in the powertrain. An electric traction system delivers power to the wheels, helping propel the car during acceleration, helping to boost the car’s fuel efficiency.

Other vehicles such as work trucks and construction equipment make use of electric hybrid technology to operate hydraulic equipment. The power to run these components is typically generated by an internal combustion engine mechanically coupled to a hydraulic pump, but by using electric hybrid technology, the hydraulics are run electrically, resulting in increased fuel efficiencies.



The diagram shows the main components of a hybrid electric vehicle powertrain.

The major electric components on an electro-hydraulic HEV include the internal combustion engine, electric generator, generator controller, battery pack, motor controller, and an electric motor coupled to a hydraulic pump.

Here, the internal combustion engine rotates the generator and creates voltage. The generator controller determines how much power and energy flow from the generator into the battery pack to be stored for later use by the powertrain or the hydraulics.

When the driver steps on the accelerator in the vehicle or adjusts the joystick to move a hydraulic actuator, a command signal is sent to the motor controller. The stored energy from the battery pack flows through the motor controller into the electric motor. The motor converts the electrical energy to mechanical energy by generating torque at a particular RPM. This power is delivered to the axle and wheels and makes the vehicle start moving. Alternatively, the power can be delivered to the hydraulic pump to build pressure and allow the driver to move, as in the case of a lift bucket, for instance.

Although differences in batteries and power electronics affect system efficiencies, the type of electric motor used is the most significant element.

Using FEA to Compare Electric Motors Designs

A finite element program for magnetic analysis was used to compare the performance of the IM and PMAC. Thousands of design scenarios were run to optimize and compare design tradeoffs between the motor types. The specifications for the designs were based on a real-world vehicle's needs.

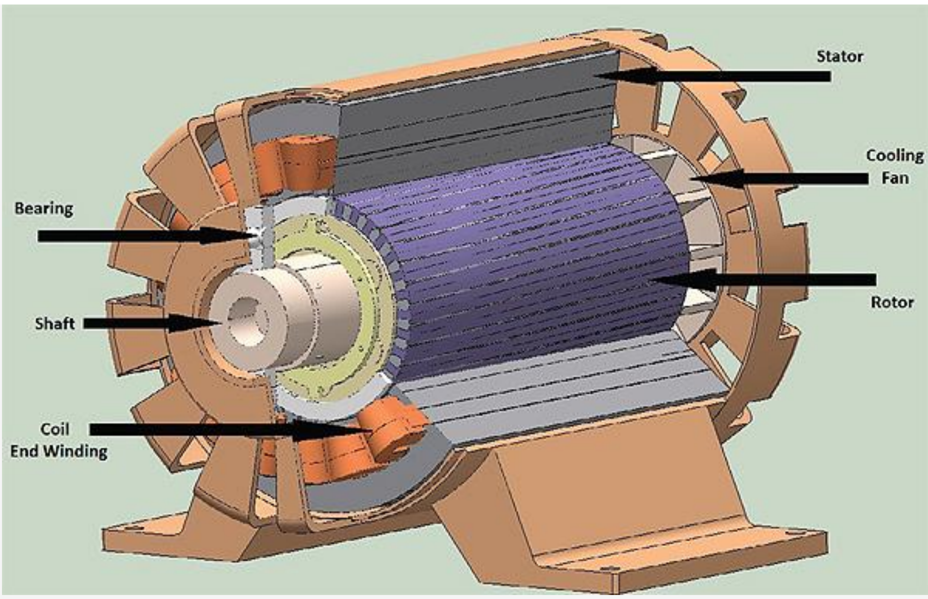
Specifications included that a motor must produce at least 600 Nm of torque and 100 kW of power on an intermittent basis. In addition, the motor needed to deliver 300 Nm of torque and 60 kW of power on a continuous basis, as well as a maximum continuous speed of 5,000 RPM to reach highway speeds. The power source was 600 VDC, 200 A RMS continuous and 400 A RMS intermittent, with the motor being water cooled.

The motors used similar materials and each was optimized for maximum efficiency, conformance to the design requirements and maximum power density.

Analyzing an Induction Motor

The torque-producing materials found in IMs are copper wires wrapped around stator laminations and rotor laminations, with insulated copper or aluminum bars inserted in the rotor laminations. A voltage in the motor windings creates current flow that produces a magnetic field. The field flows through the rotor at the same point. The motor controller switches the voltage from one winding to the next winding, causing the magnetic field to change location, and the rotor follows the magnetic field.

Based on the specifications, FEA simulations showed that an IM optimized for vehicle duty operation had a diameter of 290 mm and a length of 234.4 mm. Given those dimensions, each active component of the IM was assigned a certain weight in kilograms, with the total of all components being 72.81 kg.



The parts of an induction motor. The torque-producing materials are copper wires wrapped around stator and rotor laminations, >with insulated copper or aluminum bars inserted in the rotor laminations. *Image by: MagNet from Infolytica Corp.*

The constraints of the induction motor FEA simulation were set to run the motor at its maximum efficiency at all torque-speed points. This meant that the induction motor ran at its maximum voltage condition, allowing a better comparison to the PMAC motor.

The analysis showed that torque and power outputs of the FEA-optimized induction motor fell rapidly at the base speed. As a result, the peak and continuous power values for the induction motor just met the design criteria.

Next was the efficiency of the induction motor. An efficiency map of the motor showed it had lower efficiencies (as compared to the PMAC) across the entire operating region. This is because the induction motor needs to create both the rotor magnetic field and the stator magnetic field. Because both magnetic fields are created from the circulation of current through copper, there are significant I2R (the current squared multiplied by the resistance) losses.

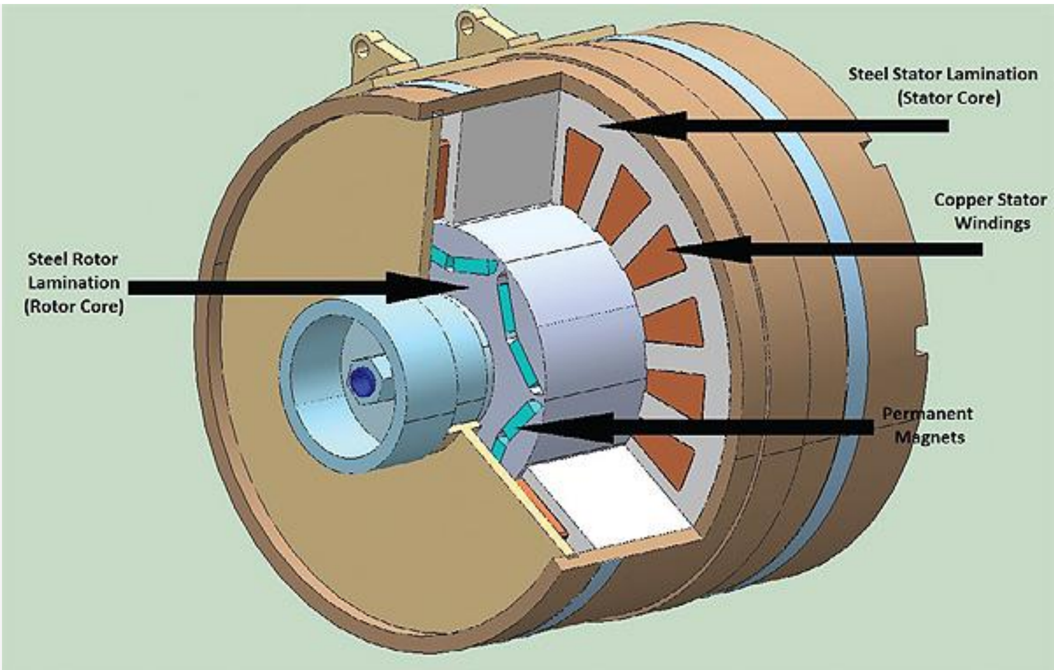
The induction motor only has copper bars on the rotor and, as a result, the motor can produce low torque values at high speed with high efficiency. At high speed and low torque, both the stator field and the rotor field can be small, so the magnetic losses are low.

Costs for each motor type were determined as well. The active materials of the induction motor are about 26% less than those for a comparable PMAC motor. The lower cost is the result of the rotor using copper bars instead of expensive permanent magnets.

Analyzing a Permanent Magnet Motor

Brushless PMAC motors have copper windings wrapped around individual laminations. The copper wire assemblies make up the diameter of the stator. The rotor is similar to the rotor used in an induction motor. However, in the PMAC motor the aluminum or copper inserts are replaced with permanent magnets.

Brushless PMAC motors work on a similar principle as the induction motor but they provide an energy savings because the magnets have a permanent field at the rotor. In contrast, induction motors require the electronics to push additional energy into the copper bars in the rotor to generate the field.



The parts of a permanent magnet AC motor. The rotor construction is similar to an induction motor but here the aluminum or copper inserts are replaced with permanent magnets. *Image by: MagNet from Infolytica Corp.*

In terms of PMAC configuration, the motor controller sends voltage and current into the copper windings. As the current switches from one winding to another, the rotor is attracted to the moving stator field. This produces the PMAC motor's torque and rotation.

Based on the specifications, FEA simulations showed that a PMAC motor optimized for vehicle duty operation had a diameter of 195 mm and a length of 326.4 mm. Here, the total weight of the active components was 49.82 kg. The study showed that the motor maintains a flat torque profile as well as the required speed. Therefore, the peak and continuous power of the PMAC motor exceed the original target values by significant margins.

An efficiency plot in this case showed that the PMAC motor is highly efficient over a significant portion of the operating region. This is a consequence of the constant magnetic field, which eliminates many of the I2R losses of the induction motor. However, the PMAC motor exhibits higher losses in a certain region (less than 60 Nm; greater than 4,000 RPM) because the rotating field from the rotor magnets produces losses in the stator. In contrast, the induction motor provides a slight increase in efficiency within the same low-torque and high-speed parameters.

In terms of cost, the PMAC's permanent magnet is made up of rare-earth materials so it is more expensive than copper. However, the magnet enables a smaller motor size and increased efficiency.

Comparing the Motors

Analysis of the optimized motor models showed that both the IM and the PMAC motor meet the necessary performance requirements. Also, although the IM is a little shorter than the PMAC motor, it is significantly heavier and has twice the volume. The maximum efficiency of the motors is close, but the IM costs 26% less than the PMAC. These results might lead one to the conclusion that the IM prevails as a result of lower cost. But what happens when each motor is placed in the drive train? As part of the study, the IM and PMAC motor FEA models were used to simulate the performance of a full electric vehicle.

The FEA software was used to determine the torque produced by the motor and the magnetic losses experienced by each motor at each point in time. Interpolation between FEA solutions was performed between torque and speed operating points that were close to each other to reduce calculation time.

The study examined "City," "Rural," and "Highway" drive cycles, based on data collected from real-life driving scenarios. The drive cycles were set such that either the IM or the PMAC motor could execute the cycle. The vehicle under study represented a light-duty Class 3 sized delivery van. The simulation results follow:

City: Average speeds are less than 7 mph and vehicle stops and starts are frequent. A 440-second segment of the simulation, which showed total battery energy used, was repeated to equate with one hour of city driving. In general, the IM losses consumed 34.6% of the total battery energy, while the PMAC motor losses consumed only 17.3% of the battery energy. Overall, the PMAC motor propelled the vehicle 27% further than did the IM while using the same amount of energy.

Rural: The average speed is about 30 mph and vehicle stops and starts are less frequent. A 1070-second segment of the simulation was repeated for an equivalent of one hour of driving under these conditions. Here, the two motors exhibited similar total energy use, but the PMAC motor was slightly better than the IM.

Highway: Average speed is about 57 mph and vehicle stops and starts are infrequent. Again, a 1070-second segment of the simulation was repeated for an equivalent of one hour of driving under these conditions. As in the rural cycle, the total battery usage was nearly the same for the two motors.

Overall, the study showed that although induction motors are less costly, the PMAC motor outperforms IMs in applications that have significant speed changes with a high change in magnitude. The PMAC is also good for OEMs needing a compact and power dense motor. Other PMAC performance advantages include better acceleration and improved gradability (a motor's capability to propel the vehicle up grades — in this case, 7%). In addition, the PMAC motor is smaller and lighter.

The data shows that the PMAC is a better choice for applications that have a highly dynamic drive cycle and that require exceptional drivability. However, induction motors are likely the preferable choice if size and weight are not significant factors or for applications in which low torque and high speeds occur for long durations.

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