Introduction to Using Hybrid-Electric Vehicle Technology
with Traditional Hydraulic Systems in Work Vehicles

Patrick Berkner

Automation Group – Electromechanical & Drives Division

2101 North Broadway, New Ulm, MN 56073, USA

pberkner@parker.com

www.parker.com/hev

INTRODUCTION

The US Environmental Protection Agency has released proposed standards that would further boost the fuel efficiency of heavy-duty trucks and buses, starting in the 2021 model year and running through 2027. The White House has cited the rules as another element in its strategy to reduce US greenhouse-gas emissions by at least 26% by 2030, compared with levels in 2005.

For heavy-duty vans and pickup trucks, fuel economy would have to rise by 2.5% a year starting in 2021.

Concern about fuel efficiency, mpg, or gph (gallons per hour) when operating a piece of construction equipment or a work vehicle were not at the forefront of developers' designs. That has changed. Now the concern is not only fuel economy and fuel prices, but the impact of greenhouse gases on the environment – especially with fuel prices being so low.

Heavy-equipment and work vehicle manufacturers have two major uses for power: moving the vehicle (traction) and hydraulics. In automotive, the answer is simple – electrify the powertrain. In work vehicles, the answer is much more complex. This complexity has led equipment manufacturers and many

One way to increase efficiency is to move from a full hydraulic architecture to an electrohydraulic system

work vehicle suppliers, who normally use full hydraulic systems, to try to find ways to make these systems more efficient. One way to increase efficiency is to move from a full hydraulic architecture to an electrohydraulic system. An electrohydraulic system is simply the integration of an electric motor (could be permanent magnet or other type with feedback) to a hydraulic pump, along with the necessary electronics and controls. This sounds somewhat simple to implement, and it can be straightforward, once the basics are understood.
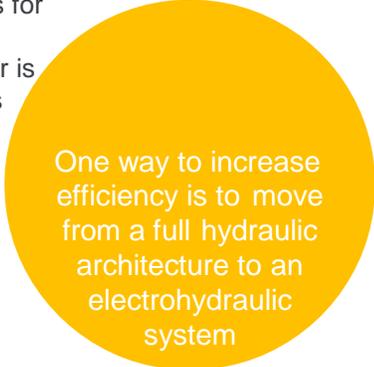
There are similarities between a hydraulic and an electrohydraulic system. Take, for example, the mechanical makeup of a hydraulic system. There is the oil reservoir, hydraulic pump and control valves. Driving this could be an IC (internal combustion) engine of some type. The comparable electric system would be a battery (for energy storage), electric motor/generator, a motor controller/inverter for controlling the motor and, again, an IC engine.

When comparing a hydraulic pump to an electric motor even the formulas for basic HP are similar:

$$HP = T \text{ (in-lbs)} \times RPM / 63,025$$

$$HP = Pressure \text{ (psi)} \times Flow \text{ (gpm)} / 1,714$$

As can be seen, motor torque corresponds to hydraulic pressure, and motor rpm corresponds to pump flow.

In a hydraulic-based, mobile system, a diesel engine (or any IC engine) drives a hydraulic pump to create hydraulic power. The hydraulic power is distributed throughout the vehicle. In an electrohydraulic system, the diesel engine will now drive an electric generator, which now generates electric power vs. hydraulic power. This electric power is distributed throughout the work vehicle. That electric power is now used to run an electric motor, which drives a hydraulic pump. The electric power is also used to run any other electric device on the vehicle, such as electric fans, e-AC units or e-power steering pumps. Any excess electric energy is stored in batteries or capacitors for later use. Or, these functions can be used when the engine is off.

When an e-motor is provided with electric energy, it converts this electric energy into rotational motion. That same electric motor can also be a generator, where rotational energy back-drives the motor, and this rotation is converted into electrical energy. This electrical energy can now be stored in batteries, much like a hydraulic accumulator stores hydraulic energy. The recapturing of energy can be realized when a load is slowed down due to gravity or momentum.

It must be noted that not all work vehicles will implement a full electrohydraulic solution.

This is dependent on the HP needed for a certain action. A typical front-end loader may use an electrohydraulic solution to raise and lower the bucket. The power required to do this may be in the 50-80hp range. That same vehicle would probably not use electrohydraulic for vehicle propulsion. Some construction vehicles need power to propel the vehicle in the 300-400hp range; most electric motors cannot supply that power easily. An electrohydraulic system on a work truck might use an e-pump in the 5-10hp range to power any number of hydraulic equipment. This is well within an electric motor's practical capability and can also be cost effective.

It is given that hydraulic system engineers are very familiar with fluid power components, what terminology is common, and how to design a very efficient system. Those same engineers may not be familiar with how the electric side of an electrohydraulic system is configured, what the terminology is, how to implement an electric motor, drive and controls on a vehicle, and ways to optimize the dual technologies for utmost efficiency.

EV & HEV COMPONENTS
AC INDUCTION TECHNOLOGY

There are a few electric motor technologies in the market. The most common are AC induction motors; the other technology is permanent-magnet AC (PMAC) motors.

Most engineers are familiar with an AC induction motor. IM technology is very mature and is by far the most common motor technology used today. It is simple to use. One merely plugs the motor into a wall outlet and the motor runs. Most water pumps, house fans and industrial-based hydraulic power supplies use this technology. The power output of an AC induction motor is from fractional HP to over 1,000hp.

One disadvantage of AC induction motors low efficiency inherent in the magnetic design, in the 75-85% range at best. Another deficiency of AC induction motors is they have a very poor power density (power (HP)/ volume), meaning they are large and heavy relative to the amount of power they can produce. A motor controller/inverter can be connected to these motors to allow them to run at a variable speed. The electronics is relatively inexpensive to operate an AC induction motor.

A major advantage of an AC induction motor is its low cost. AC induction motors use outer copper coils and iron or copper bars on the motor's rotor to cause motor rotation. There are no magnets in an AC induction motor. Due to the absence of magnets, this motor is relatively

> Due to the absence of magnets, this motor is relatively inexpensive, compared with a permanent-magnet AC motor

inexpensive compared with a permanent-magnet AC motor, which will be discussed next. Since there are so many of these motors produced yearly, they are commodity items.

PMAC SERVO MOTOR TECHNOLOGY

The permanent-magnet AC servo motor (PMAC), on the other hand, is a newer technology. The term "servo" is a controls term and has to do with feedback and closed-loop control. The PMAC servo motor allows users to have very high closed-loop control of speed, direction and torque. PMAC motors are very efficient (90%+), and have outstanding torque density – torque per unit size. The output range of the technology is a bit smaller than AC motors. The range tends to be fractional horsepower to 400hp.

By examining a cutaway of a PMAC servo motor, the copper coils are to the outside of the motor. The rotor, however, has permanent magnets placed on or in the rotor. It is the magnets and the winding technology of the coils that give the motor its higher torque density compared with an AC induction motor.

A feedback device is typically located on the rear of the motor. Most PMAC servo motors must have a feedback device in order to commutate the motor correctly. The feedback device, along with the necessary circuitry in the motor controller/inverter and the permanent magnets, make PMAC motor designs more expensive, but with very high dynamics. There are motor controller/inverters available that take advantage of "sensorless technology." This technology uses the motor's back-emf voltage, and phase current to determine the position of the rotor, and is able to commutate the motor without the use of an actual feedback device. Sensorless technology could be used in applications such as electric fans or electrohydraulic pumps with low fluid control dynamics. This technology applies to applications that are only required to run in velocity mode.

The following table compares the power density, weight and price of the two motor technologies. Note how the power density of the PMAC servo motor is two to three times more than the AC induction motor, and also two to four times lighter. However, the PMAC servo is also 1.5 – 2 times more expensive than the AC induction motor.

Due to the superior power density and the lighter weight of the PMAC servo motors, this is the motor of choice for most hybrid vehicles and e-pump applications.

Table 1. Motor technologies – power density, weight and price

Motor Technology	HP	Power Density (HP / in^3)	Weight (lb)	Price
AC induction	5	.007	95	$970
AC induction	10	.006	170	$1,561
PMAC servo	5	.023	24.3	$1,550
PMAC servo	10	.042	29.3	$1,950

Cubic area, weight and price are averaged over multiple motor sizes. Data per Parker and Baldor specifications.

MOTOR CONTROLLER/INVETER TECHNOLOGY

A PMAC servo motor and an AC induction must use a motor controller/inverter to run the motors at varying speeds. The size of the amplifier is dependent on the current rating of the motor. The servo amplifier usually has the same or greater output power than the motor it is attached to. As an example, a PMAC servo motor that requires 10A of rated current would normally have a 10A (or larger) amplifier to control it. Motor controllers can operate at various voltage levels from 12-800V DC, and come in various power levels. It is not possible to state a standard voltage for any work vehicle due to the variables in each vehicle and vehicle vendor. One vehicle may specify 280V DC; the next may specify 600V DC. However, when specifying an operating voltage range for a mobile system, there is one point to remember: the higher the voltage, the less current that is required. As an example, a function on a mobile vehicle may require 20hp (15kW) of power. If it is decided to use a 100V DC system, the motor controller must produce 150 amps of current, using the formula:

Power = volts x amps

However, if the system can increase the voltage to 600V, the current requirement from the

controller is now 25A. The higher the system voltage, the less current that will be required. Current is a cost driver for motor controllers.

Most motor controllers/inverters are rated to run in an ambient environment of 40ºC. The amplifier temperature must not exceed this rating or the amplifier will need to reduce current to the motor, or shut itself down entirely. This may require special cooling techniques such as forced air, water glycol cooling or an AC cooling system for the system electronics. Since this device will be installed onto a mobile vehicle, special consideration must be given to the robustness of the motor controller. Inverters designed for the mobile market are rated for higher shock and vibration ratings. These "mobile-hardened" components are tested per SAE J1455 specifications. It is imperative that standard industrial-rated amplifiers not be used in mobile applications due to the additional failure modes present in the work vehicle environment.

BATTERIES

Most mobile vehicles must use some type of energy storage device. The most common storage device is a battery pack.

There are three common battery technologies in use today: lithium-ion, nickel-metal hydride and lead-acid. Each of these can be graded on energy density, measured in Wh/Kg (watt-hour per kilogram), voltage, recharge time, weight, volume and cost.

The following table compares the power density of all three motor technologies and the cost of each.

Table 2. Motor technologies – power density and cost

Battery Tech.	Energy (Wh/Kg)	Cost ($ Kw-hr)
Lithium-ion	140	$770
Nickel-metal hydride	110	$880
Lead-acid	50	$100

Even though lithium-ion batteries have a higher energy density, they are almost eight times more expensive than the lead-acid. However, the lithium-ion has three times more energy per kilogram than the lead-acid, meaning it packs more energy per size.

Lead-acid batteries are more readily available than nickel-metal hydride and lithium-Ion. Local automotive supply stores carry lead-acid batteries, but the other technologies are more difficult to procure.

Although lead-acid are cheaper, they have significant performance disadvantages compared with the other technologies, including cycle life, partial state of charge operation, and charge acceptance rate. Lead-acid simply won't work in many types of vehicles. Misapplication will result in having to frequently replace the pack.

The batteries themselves are only part of the equation. One must have a way to charge the batteries using a matched charger, and a BMS (battery management system) to manage the charge rate and time to ensure damage does not occur. Independent of the battery technology, there are always multiple batteries in an electrohydraulic system. In order to have a system voltage of 300V DC, and depending on the amount of current to be supplied, a lead-acid battery configuration may take more than 25 batteries – requiring the vehicle to be able to manage the size and weight; a lithium-ion configuration could take more than 100 smaller cells with complexity, but more effective use of weight/volume. The BMS determines which batteries need to be charged in the system, and it is also able to detect any battery shorts. A short in a single battery will draw all the current from the battery charging system, leaving the other batteries to slowly lose their total charge.

The battery charger can be a simple plug-in unit. However, in certain applications, the conversion of kinetic to electrical energy, such as back-driving the motor, or if the IC engine is turning the generator, will also charge the batteries and require additional features.

There is another electrical storage device called a "super-cap" or ultra-cap." This device is a high-power electric capacitor and works like a hydraulic accumulator. The reason to use a super cap is it is able to accept very high charge rates for short durations and can quickly release that stored energy.

Although lead-acid are cheaper, they have significant performance disadvantages compared with the other technologies

IMPLEMENTATION OF AN ELECTROHYDRAULIC SYSTEM

Now that the major electronic components are known for an electrohydraulic system, the question must be raised as to why to integrate an electrohydraulic system? What are the benefits to this design vs. a standard engine-driven hydraulic system? There are many benefits, and each has more weight depending on the actual application. Some reasons to integrate an electrohydraulic system are:

1) Engine optimization with energy recovery and storage

2) Variable-speed, fixed-displacement efficiency

3) Power on demand

4) Reduced emissions.

1) ENGINE OPTIMIZATION WITH ENERGY RECOVERY AND STORAGE

In a typical hydraulic application, the engine is sized such that it has at least enough power to drive the hydraulic pump, along with any propulsion requirements. A large front-end loader or a smaller skid-steer loader is an example of this. When operating this equipment, the engine is usually running at full speed whether moving the loader or raising and lowering the bucket. Similar operation is true in a work truck where the vehicle is stationary and the engine runs at high idle to provide enough speed to operate the hydraulic pump. If a manufacturer is able to add an electrohydraulic system that is only used to raise and lower the bucket and not use the engine to do this, you would save energy. The way this is accomplished is to attach an electric generator (motor) to the diesel engine. When the engine is running, it is charging the batteries. The stored energy in the batteries is then fedback to electric motors, which rotate the gear pumps to control the lifting and tilting of the bucket. In actual operation, as the bucket is raised, energy is being used from the batteries However, when the bucket is being lowered, that kinetic energy from the bucket is back- driving the hydraulic pump, which is coupled to the servo motor. The motor is now being run as a generator. This rotational motion is being converted to electric energy and is being put back into the batteries through the drive. That energy is stored for the
next time the bucket is raised. Since the electric motors have "off-loaded" some of the necessary power from the engine, the size of the engine can be decreased, resulting in fuel and emissions savings.
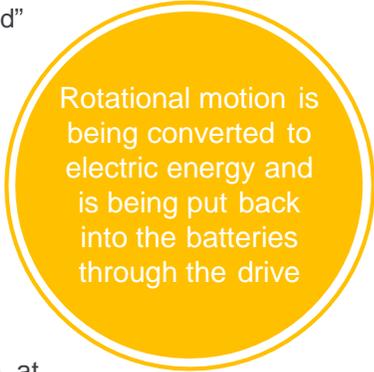
Rotational motion is being converted to electric energy and is being put back into the batteries through the drive

2) VARIABLE-SPEED, FIXED-DISPLACEMENT EFFICIENCY

A fixed-displacement pump is one of the more efficient hydraulic pumps available with efficiencies in the 96% range. If that pump is now attached to an electric motor and run at variable speeds per the application, there can be energy savings. If the same hydraulic front-end loader or skid steer is used, and the engine is again being run at

max speed, even though the bucket is being raised very slowly, energy is still being wasted. If the gear pump and servo motor can now be run at variable speeds to match the application requirements and the bucket is being raised, the electric motor will run at "x" speed. If the bucket is being tipped, the motor can speed up to maybe 2x, resulting in more hydraulic fluid flow. The hydraulic pump and electric motor will only run when needed, and run at the necessary speed.

*It should be noted that like a diesel engine, there is an optimal efficient speed range to run the electric motor and generator. In the graph to the right, the motor is more than 90% efficient from 1,500 to 5,000rpm. Running less than 1,500rpm will decrease the system efficiency.
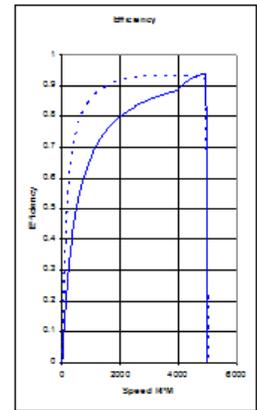

Figure 1. Optimal efficient speed range

3) POWER ON DEMAND

With any electrohydraulic system, the pump/servo motor are run only when needed. The IC engine will only need to run when charging the batteries. A PMAC servo with a hydraulic pump can accelerate from zero to its rated speed in 20ms typically. That is fast enough for most hydraulic systems and this slight delay is not noticeable to the system operator. This is especially useful for trucks that have relatively low power and duty cycles on the hydraulics. The systems could run with engine completely turned off.

4) REDUCED EMISSIONS

Reduced emissions ties in with energy recovery and storage. The Tier IV requirements are well known and are being fully implemented. They specify a maximum amount of particulates and gases that can be emitted from the engine. This reduction in particles and gases can be done by reducing the size of the engine, possibly using a smaller engine or running the engine less. In an electro-hybrid system, the motor (or generator) is attached to the diesel engine. This can be done through a flywheel attachment, PTO, or even a belt and pulley system. The engine is run only to generate electric power. This power is now stored in the batteries. Once the battery system is charged, the engine is turned off until the batteries are depleted again.

See Figure 2 on the next page.

EXAMPLE OF AN ELECTROHYDRAULIC SYSTEM

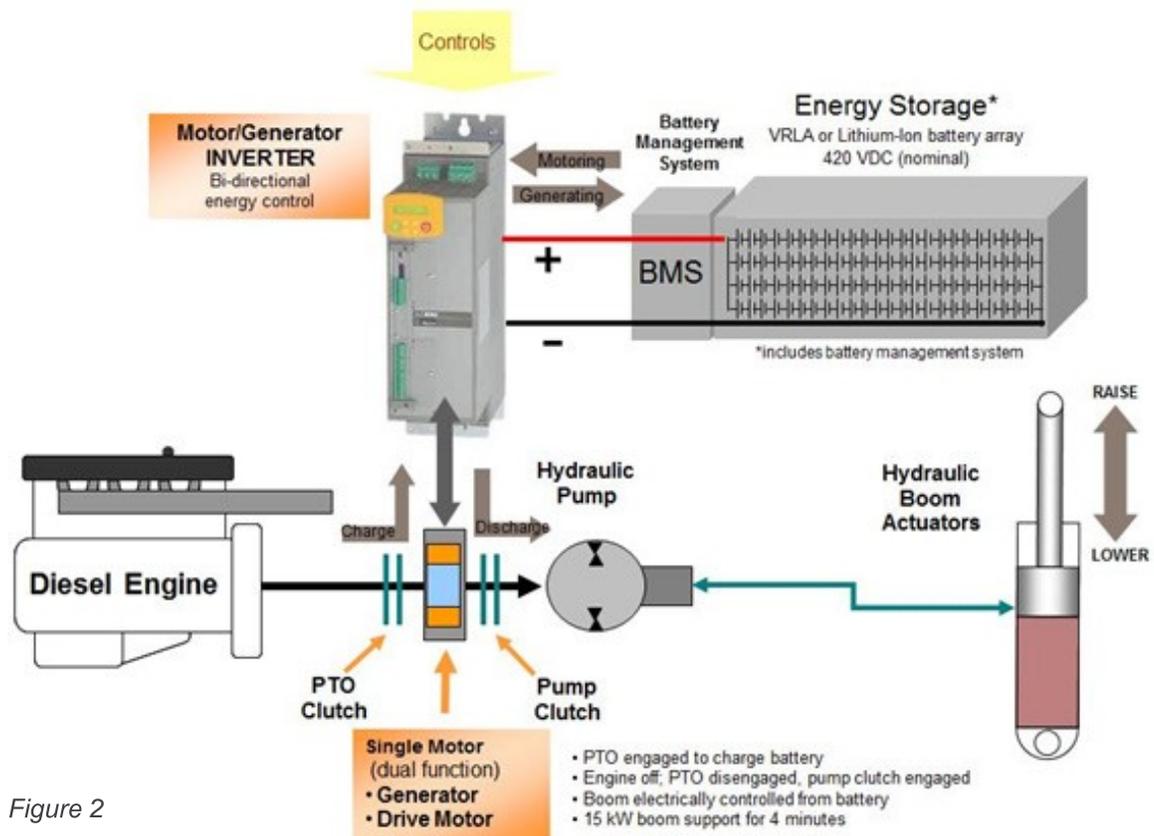Implementation of an electrohydraulic system used to cycle a boom actuator

Figure 2

The system consists of the diesel engine coupled through a PTO. The PTO is disengaged when the engine is running at high speed, such as driving at highway speeds. The e-motor has a dual purpose: 1) To act as a motor and rotate the hydraulic pump, and 2) Work as a generator to charge the batteries when necessary. Notice there is the possibility to add a clutch between the generator and pump. This gives the operator the ability to generate and run the hydraulic pump off the diesel engine if needed (if the batteries are not charged at that time).

When the engine is running the generator, the power from the generator goes to the amplifier. The amplifier is converting this three-phase AC sine wave into a DC voltage compatible with the batteries. Note the battery management system that must be used.

The BMS along with the amplifier are used to charge the batteries. When the batteries are charged, the engine can be shut down. When needing to run the hydraulic pump, the power from the batteries now flows into the amplifier and is used to rotate the servo motor and pump hydraulic fluid on demand. At some time, the energy in the batteries will be depleted. At that time, the diesel engine will start up and charge the batteries, and/or run the hydraulic pump until the batteries are fully charged.

One item that is not explained in detail is the control system. A CAN-based control system must be used to synchronize all control signals between the engine and the electric amplifier. Most vehicles use the J1939 standard for this communication.

EXAMPLE OF APPLICATION AND VALUE-IN-USE ESTIMATION

When specifying a PMAC motor/generator, there are a number of items that must be known in order to correctly determine the servo motor to use for an application:

a) **Speed** – this is the speed of the hydraulic pump that is driven by this motor

b) **Torque** – this is the torque required by the hydraulic pump to generate the specified pressure at a specified flow rate

c) **Voltage** – voltage level for controllers and batteries

d) **Ambient temperature** – this is used to determine if the motor can run within its operating range

e) **Size** – space limitations or the area the motor must fit into

The speed and torque requirements of the motor are determined by the hydraulic pump that will be attached to the motor. In this example, the system needs 8gpm at 2,000 psi. We will assume a 300V DC system, just for ease of calculations. We know the motor needs to run at a rated speed of 2,000rpm; now we need to figure out how much torque will be required from the motor. The basic formula for HP is:

$$HP = Pressure\ (psi)\ x\ Flow\ (gpm)\ /\ 1,714$$

In this example, the calculated HP is 9.33. The torque required for the motor can now be calculated using the same HP formula, only calculating for torque:

$$HP = T\ (in\text{-}lbs)\ x\ rpm\ /\ 63025$$
$$T = HP\ *63,025\ /\ rpm$$
$$T = 9.33\ *\ 63,025\ /\ 2,000$$
$$T = 294\ in\ lb\ (33Nm)$$

The requirements from the motor are 294 in-lbs (33Nm) at 2,000rpm.

The specifications for a standard PMAC motor are 325 in-lbs at 2,500rpm. The current required for this motor is 28.5A RMS; again, that is from the catalog.

If optimal efficiency or current optimization were not the object with this application, this motor selection would stop here. However, for the sake of this exercise, optimal efficiency and current optimization will be reviewed.

The efficiency curve shows 90% efficiency over the speed range. Even though this motor is rated for 2,300rpm, and the requirement is 2,000rpm, there is no reason, based on this efficiency graph, to modify the motor to gain a fraction of an efficiency point. However, it is possible to decrease the current requirement if the motor's winding is optimized to run at 2,000rpm vs. 2,500.

In order to do this, the motor's windings are wound with a different number of turns of wire, and different gauge wire in the stator. Changing the number of turns will change a parameter called Ke. Ke is calculated using the following formula:

Figure 1. Optimal efficiency speed range

$$Ke\ (volts/Krpm) = Drive\ Voltage\ *\ 1,000\ /\ maximum\ motor\ rpm$$

This means if this motor is back-driven at 1,000rpm (as a generator), it would create a voltage of a certain value at the motor terminals.

The standard GVM142XXXXB has a Ke = 79 v(rms)/Krpm. Using the Ke formula above, and in order to have a rated speed of 2,000rpm, the new winding must have a Ke of 100 volts (rms) / Krpm.
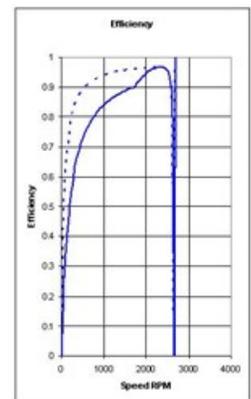
The necessary units have been changed between V DC and volts rms (300V DC = 212 volts rms). A rated speed of 2,000rpm must have a max speed = 2,120rpm.

$$Ke = 212{,}000 / 212 \qquad = 100 \text{ volts rms} / Krpm$$

There is a direct correlation between Ke and Kt. Kt is used to determine for a given amount of current, the amount of torque produced by the motor. The conversion formula is:

$$Ke \text{ (Vrms/Krpm)} * .146379 = Kt \text{ (in-lbs/amp rms)}$$

The GVM142XXXXB standard motor has a Kt = 11.59 in-lbs / amp rms

The higher the Kt of a motor, the less current will be required to generate a certain amount of torque. However, the higher the Kt of a motor, the slower the motor will run for a given bus voltage, so there is a tradeoff between speed and current.

In this example the motor with a Ke = 100 volts rms/Krpm has a Kt = 14.6 in-lbs/amp. For every amp of current into the motor, 14.6 in-lbs of torque will be produced.

This application needed 294 in-lbs at 2,000rpm. Therefore 294 amps / 14.6 = 20.1A is what the application needs. If we had used the original standard motor without modifying the windings, this application would have needed 25.4A to generate the necessary torque (294 / 11.59). Creating a motor with an application specific winding uses 21% less current for the same application.

This has a direct reduction in the size of the amplifier, and the size and/or number of batteries needed for energy storage in this system, or the operating time of the vehicle under electric operation.

POSSIBLE APPLICATIONS AND DEVELOPMENTS

There were four reasons above as to why to use electrohydraulic actuation for work vehicles. The limiting factor to the power output of an electric motor is size. One way to reduce the size of an e-motor is to improve on its cooling. If the motor is unable to dissipate enough heat, the motor will overheat. Most electric motors for the mobile market do implement a water (or oil) cooling technology of some type. A 15kW motor can output up to 60kW by water cooling the motor/generator. Assume 70⁰C water at a 2gpm flow rate. This allows the manufacturer of the mobile vehicle to reduce the overall size of the motor, since a smaller motor/generator can now output more power. Along with the water-cooled motor/generator comes the requirement to water cool the motor controller. Another way to cool the motor/generator is to actually immerse the motor in an oil bath. Oil can be allowed to flow through the motor windings for added cooling. A vehicle manufacturer can actually put the motor inside the vehicle's transmission, flooded with oil, to get the benefits of liquid cooling. An issue to deal with would be the temperature of the transmission fluid. The higher the temperature of the oil, the lower the increase in power.

CONCLUSION

As can be seen in this paper, and with the example of sizing a motor/generator, the addition of an electrohydraulic system is fully possible, and fully beneficial to the vehicle manufacturer and operator. It is not uncommon for a 30-40% (or more) energy savings for a power-on-demand system to be realized. The other benefits are in reduced emission, "silent operation" and possible engine downsizing. Parker Hannifin has all the necessary technology to help transition nearly any vehicle's pure hydraulic systems to a hybrid system using electric technology. Contact Parker today at www.parker.com/hev to learn more.