

How, Why, and When to apply electric motors to mobile hydraulic systems

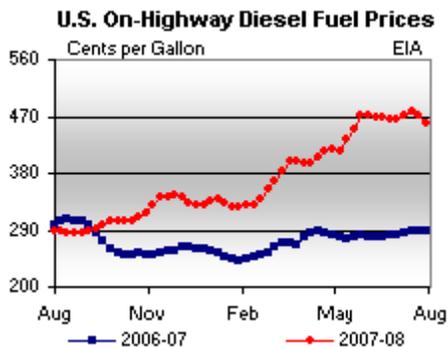
Patrick Berkner

Automation Group – Electromechanical Automation Division
2101 North Broadway, New Ulm, MN 56073
pberkner@parker.com

Keywords: (i.e., fuel reduction, efficiency, emissions, on-demand)

Introduction

The price of fuel has almost doubled over the last year and a half. Up to this point, fuel has been relatively inexpensive. Most companies weren't concerned about fuel conservation, fuel efficiency, mpg, or gph (gallons per hour) when operating a piece of construction equipment or a mobile vehicle. That has changed. Now the world has record high fuel prices and fuel conservation and fuel efficiency are openly being discussed.



This has led construction equipment manufacturers and any mobile vehicle suppliers, who normally are using full hydraulic systems, to try to find ways to make their hydraulic systems or mobile vehicles more fuel efficient. We all know about the Toyota Prius hybrid automobile, but what about the Caterpillar D9E electric dozer? There are now more mobile

equipment manufacturers moving from full hydraulics to electro-hydraulic systems. A electro-hydraulic system is simply the integration of an electric motor or servo motor 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 behind an electro-hydraulic system.

There are similarities between a hydraulic and an electro-hydraulic 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 storage), electric servo motor / generator, an amplifier (or 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 is similar.

$$HP = T \text{ (in-lbs)} \times \text{RPM} / 63025$$

$$HP = \text{Pressure (psi)} \times \text{Flow (gpm)} / 1714$$

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 electro-hydraulic 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 mobile vehicle. That electric power is now used to run an electric motor, which now drives a hydraulic pump. The electric power is also used to run any other electric device on the mobile vehicle, such as electric fans, AC units, or power steering pumps. Any excess electric energy is stored in batteries or capacitors for later use.

When a servo motor is provided with electric energy, it converts this electric energy into rotational motion. That same electric motor can also be a generator, whereas 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.

It must be noted that not all mobile vehicles will implement a full electro-hydraulic solution.

This is dependent upon the HP needed for a certain action. A typical front-end loader may use an electro-hydraulic solution to raise and lower the bucket. The power required to do this may be in the 50 – 80 HP range. That same vehicle would probably not use electro-hydraulic for vehicle propulsion. Some construction vehicles need power to propel the vehicle well in the 300 – 400 HP range; most electric motors can not supply that power easily.

It is common for most hydraulically experienced engineers to be very familiar with how a hydraulic system is configured, what the terminology is, and how to implement a hydraulic system. Those same

engineers may not be familiar how the electric side of a hydro-electric system is configured, what the terminology is, or how to implement an electric motor, drive, and controls on a vehicle. The components of the electric side of hydro-electric will now be discussed.

Electric Motors

AC Induction Technology

There are a few electric motor technologies in the market. The most common are AC induction motors, and the other technology is AC servo motors.



Most people are most familiar with an AC induction motor. That motor technology is very old and is by far the most common motor technology out there.

It is simple to use. You merely plug 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 1000 HP. The disadvantages of AC induction motors are they are a low energy efficient motor, in the 70% - 80% 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 it can produce. A drive or inverter can be connected to these motors to allow the motors to run at a variable speed. This drive is relatively inexpensive to operate an AC induction motor.

A major advantage to an AC induction motor is its low cost. AC induction motors use outer copper coils and iron 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 inexpensive, compared to a permanent magnet AC motor, which will be discussed next. Since there are so many of

these motors produced yearly, it is a commodity item.



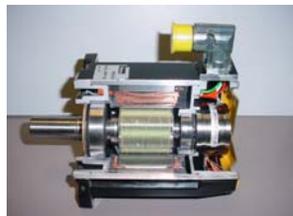
AC Servo Motor Technology

The permanent magnet AC servo motor, on the other hand, is a newer technology, is very efficient (90%+), and has a very high torque density.— it has a more torque relative to the size of the motor. The disadvantage to this design is it has lower power output. The power output of an AC servo motor is from fractional HP to 100 HP. This is the motor technology currently being produced by Parker's Electromechanical Automation Division.



If we look at the cutaway of an AC servo motor, the copper coils are to the outside of the motor. The rotor, however, has permanent magnets bonded onto it. It is the magnets and the winding technology of the coils that give the motor its higher torque density compared to an AC induction motor. Yet due to the permanent magnets, the cost of this motor is higher.

Also notice the feedback device to the right of the rotor. All AC servo motors must have a feedback device in order to commutate the motor correctly. This feedback device, along



with the necessary circuitry in the amplifier and the permanent magnets, makes this motor design more expensive.

The following table compares the power density, weight, and price of the two motor technologies. Note how the power density of the AC servo motor is 2 – 3 times more than the AC induction motor and also 2 – 4 times lighter also. However, the AC servo is also 1.5 – 2 times more expensive than the AC induction motor.

Because of the superior power density and the lighter weight of the AC servo motors, this is the motor of choice for the electro-hydraulic vehicles which Parker has been involved in.

| Motor Technology | HP | Power Density | Weight | Price |
|------------------|----|----------------------|--------|--------|
| | | HP / in ³ | lbs | |
| AC Induction | 5 | .007 | 95 | \$970 |
| AC Induction | 10 | .006 | 170 | \$1561 |
| AC servo | 5 | .023 | 21 | \$1400 |
| AC servo | 10 | .013 | 89 | \$3100 |

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

AC Amplifier / Inverter

An AC servo motor and an AC induction must use an amplifier (or inverter) to run the motors at a variable velocity. The size of the amplifier is dependent upon the current rating of the motor it is connected to. The servo amplifier usually has the same or greater output power than the motor it is attached to. As an example, an AC servo motor that requires 10 amps of rated current would normally have a 10 amp (or larger) amplifier to control it. Servo amplifiers can operate in various voltage levels from 12 - 640 volts DC, and come in various power levels. It is not possible to state a standard voltage for any mobile vehicles due to the variables in each vehicle and vehicle vendor. One vendor may specify 280 volts DC; the next may specify 600 volts 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 15 kW of power. If it is decided to use a 100 volt DC system, the amplifier must produce 150 amps of current, using the formula:

$$Kw = \text{volts} \times \text{amps}$$

However, if the system can increase the voltage to 600 volts, the current requirement from the amplifier is now 25 amps. A rule of thumb when deciding to use a servo amplifier is this: "*Voltage is cheap, current is expensive.*" In other words, the higher the system voltage, the less expensive the amplifier, since it will require less current.

Most servo amplifiers are rated to run in an ambient environment of 40 degrees C. Knowing this, the amplifier temperature must not exceed this rating. This will 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 servo amplifier. Amplifiers designed for the mobile market are rated for higher shock and vibration ratings. It is imperative that standard industrial-rated amplifiers not be used in mobile applications.

Batteries

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

There is no single type of battery technology to use in a mobile hybrid vehicle. There are three common battery technologies in use today: lithium ion, nickel-metal hydride, and lead acid. Each of these can be graded upon power density, measured in w-hr/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.

| Batty Tech. | Energy W-hr/Kg | Cost \$.Kw-hr |
|----------------------|----------------|---------------|
| Lithium Ion | 140 | \$770 |
| Nickel-metal Hydride | 110 | \$880 |
| Lead Acid | 50 | \$100 |

Design News 8-28-08

Even though lithium ion batteries have a higher energy density, they are almost 8 times more expensive than the Lead Acid. However, the lithium ion has 3 times more energy per Kg 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. A local hardware store carries lead acid batteries, but the other technologies are more difficult to procure.

The batteries themselves are only part of the equation. You must have a way to charge the batteries using a battery charger, and you must have the BMS (Battery Management System) to do that. Independent of the battery technology, there are always multiple batteries in an electro-hydraulic system. In order to have a system voltage of 300 volts DC, and depending on the amount of current to be supplied, a lead acid batter configuration may take more than 25 batteries; a lithium-ion configuration could take more than 100. 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 charger, leaving the other batteries to slowly lose their total charge. The BMS requires a connection to every battery terminal, so it does tend to be a wiring issue with a higher voltage system due to the number of batteries that must be used. The BMS is also a technology in itself.

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.

There is another electrical storage device called a "super-cap." This device is a high power electric capacitor (hence the

name) and works like a hydraulic accumulator. The reason to use a super cap is it is able to take a recharge very quickly (less than one second) and it is also able to release that stored energy quickly. It is not meant for long-term electrical storage like a battery.

Implementation of an electro-hydraulic system

Now that the major electronic components are known for an electro-hydraulic system (servo motor, drive, batteries), the question must be raised as to why build an electro-hydraulic system. What are the benefits to this design vs. a standard straight engine driven hydraulic system? There are many benefits, and each benefit has more weight depending upon the actual application:

- 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.

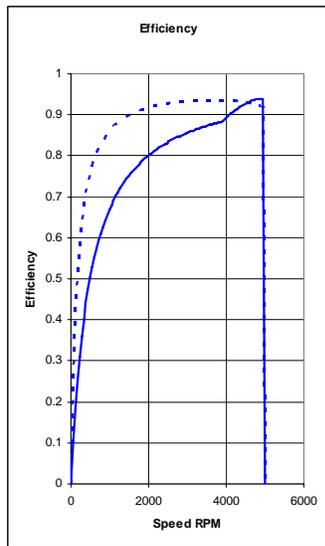
In a typical hydraulic application, the engine is sized such that it has at least enough power to drive the hydraulic pump, along with any propulsion requirements. A large front-end loader or a smaller skid-steer loader is an example of this. When running this equipment, the engine is usually running at full speed whether moving the loader or raising and lowering the bucket. If a manufacturer is able to add an electro-hydraulic system that is only used to raise and lower the bucket and not use the engine to do this, you could potentially 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 fed back 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 (assuming they are charged). 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 and battery management system. 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, and this will result in fuel savings.

- 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 servo 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 a variable speeds to match the application requirements and the bucket is being raised, the electric motor will run at "x" speed. Now if the bucket is being tipped, the motor can speed up to maybe 2x, resulting in more hydraulic fluid flow. The gear 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 servo motor / generator. In the graph to the right, the motor is more than 90% efficient from 1500 to 5000 rpm. Running less than these speeds will decrease the system efficiency.



generate electric power. This power is now saved in the batteries. Once the battery system is charged, the engine is turned off until the batteries are depleted again.

3) Power on demand

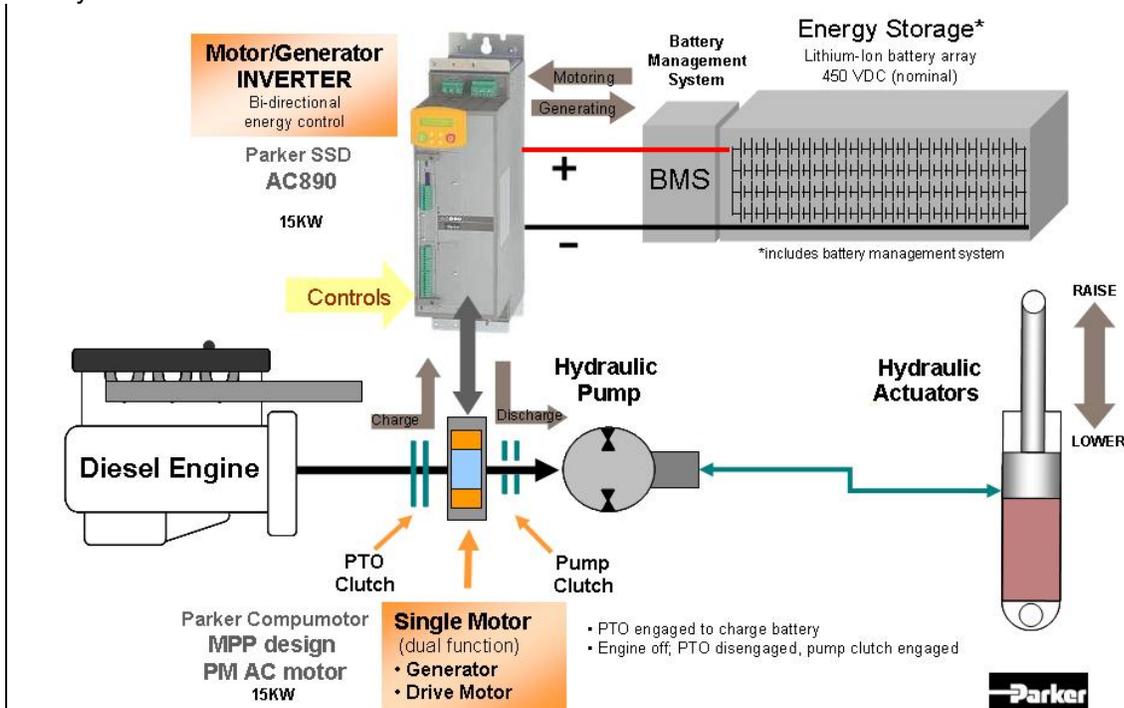
With any electro-hydraulic system, the pump / servo motor are run only when needed. The IC engine will only be running to charge the batteries when needed. Unlike an IC engine / hydraulic pump, hydraulic fluid is always flowing and just porting back to the reservoir, unless the engine is shut off. If the diesel engine is not running, it is not using any fuel. An AC servo with a hydraulic pump can accelerate from zero to its rated speed in 20ms typically. That is usually fast enough for most hydraulic systems and this slight delay is not noticeable to the system operator.

4) Reduced emissions

The reduced emissions ties in with energy recovery and storage item. The Tier IV requirements are well known by now. It specifies a maximum amount of particles and gasses that can be emitted from the engine. This can be done by possibly using a smaller engine or running the engine less. In another electro-hybrid system, the motor (or generator in this case) is tied 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

Example of an electro-hydraulic system

The following figure shows a possible implementation of an electro-hydraulic system used to cycle a boom actuator.



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 motor has a dual purpose: 1) to act as a motor and rotate the hydraulic gear 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 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.

On the flip side, when the batteries are charged, the engine can be shut down. 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 to a certain point. 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 much detail (if at all) is the control system. This is due to the inexperience of the author when working with the IQAN system. An IQAN system or suitable control system must be used to synchronize all control signals between the engine and the electric amplifier.

Example of application and value-in-use estimation

When specifying an AC servo motor / generator, there are a number of items that must be known in order to correctly determine the size 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 8 gpm at 2000 psi. We will assume a 300 volt DC system, just for ease of calculations. We know the motor needs to run at a rated speed of 2000 rpm; now we need to figure out how much torque will be required from the motor. The basic formula for HP is:

$$\text{HP} = \text{Pressure (psi)} \times \text{Flow (gpm)} / 1714$$

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:

$$\begin{aligned}\text{HP} &= T \text{ (in-lbs)} \times \text{RPM} / 63025 \\ T &= \text{HP} * 63025 / \text{RPM} \\ T &= 9.33 * 63025 / 2000 \\ T &= 294 \text{ in lbs}\end{aligned}$$

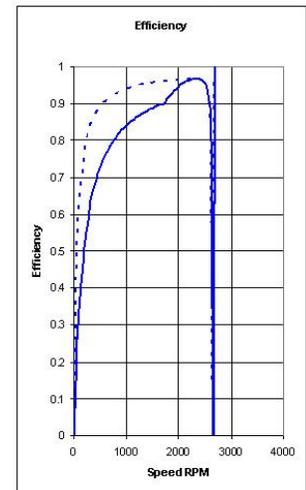
The requirements from the motor are 294 in-lbs at 2000 rpm.

The specifications for an AC servo motor are 325 in-lbs at 2500 rpm*.

*Standard MPP1906B servo motor from std. catalog.

The current required for this motor is 28.5 amps RMS; again, that is from the catalog. If optimal efficiency or current optimization were not the object with this application, this motor sizing could stop here. However, for the sake of this exercise, optimal efficiency and current optimization will be reviewed.

The efficiency curve below shows 90% efficiency over the speed range. Even though this motor is rated for 2300 rpm, and our requirement is 2000 rpm, there is no reason, based upon 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 2000 rpm vs. 2300.



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

$$K_e \text{ (volts/Krpm)} = \text{Drive Voltage} * 1000 / \text{maximum motor rpm.}$$

This means if this motor is back driven at 1000 rpm (as a generator), it would create a voltage of a certain value at the motor terminals.

The standard MPP1906B has a $K_e = 79 \text{ v(rms)/Krpm}$. Using the K_e formula above, and in order to have a rated speed of 2000 rpm, the new winding must have a $K_e = 100 \text{ volts (rms) / Krpm}$.

The necessary units have been changed between volts DC and volts rms (300 Vdc = 212 volts rms). A rated speed of 2000 rpm must have a max speed = 2120 rpm.

$K_e = 212000 / 212 = 100$ volts rms / Krpm.

number of batteries needed for energy storage in this system.

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

K_e (Vrms/Krpm) *.146379 = K_t (in-lbs/amp rms).

The MPP1906B standard motor has a $K_t = 11.59$ in-lbs / amp rms

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

In this example the motor with a $K_e = 100$ volts rms/Krpm has a $K_t = 14.6$ 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 2000 rpm. Therefore $294 \text{ amps} / 14.6 = 20.1$ amps is what the application needs. If we would have used the original standard motor without modifying the windings, this application would have needed 25.4 amps to generate the necessary torque ($294 / 11.59$). Creating a motor with a custom 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

Possible applications and developments

There were four reasons above as to why use electro-hydraulic actuation for mobile vehicles. Currently, there is testing taking place on front-end loaders, hydraulic lifts, excavators, and passenger busses. The limiting factor to power output on an AC servo motor is size. One way to reduce the size of an AC servo motor is to improve upon its cooling. If the motor is unable to dissipate enough heat, the motor will overheat. There are developments taking place to use water cooled (water / glychol)

or oil to cool the motors. A 15 KW motor can output up to 60 Kw by water cooling the motor / generator. Assume 70 degrees C water at a 2gpm flow rate. This allows the manufacture 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 servo amplifier and that development is taking place also. 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 of the vehicle's transmission, flooded with oil, to get benefits of the liquid cooling. An issue to deal with would be the temperature of the transmission fluid. The higher the temperature of the oil, the smaller the increase in torque. An increase in power of two to three times is realistic; a five time increase is not when using a submerged solution.

Full electric vehicles, with no hydraulics, are also being developed using the same electronics (motor / generator, drive, batteries) to power a large passenger bus. The same reasons apply for this application. The manufacturers want energy

savings, power on demand, and reduced emissions.

Conclusion

As can be seen in this paper, and with the example of sizing a motor / generator, the addition of an electro-hydraulic system is fully possible, and fully beneficial to the vehicle manufacturer and operator. It is not uncommon for a 40% (or more) energy savings for a power on demand system or maybe only 5%, depending upon the application of course. But the idea is to know it is possible to do, and Parker is

working on these applications now. This white paper was written as a primer for the hydraulics-fluent engineer and designer to get a general understanding of the involvement required when adding an electrical motor system to a mobile vehicle. There are many items that were not touched upon, such as safety requirements and a number of other standards that are too numerous to mention. There are items that the author is not fully familiar with, such as the Parker IQAN or controller system.