Hydraulics & Pneumatics

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Hydraulic-Electric Analogies: DC Motors and Hydraulic Motors

Many similarities are apparent when comparing series-connected dc motors to pressure-compensated hydraulic motors.

Given that a series-connected electric dc motor and a pressure-compensated hydraulic motor have the same speed and torque ratings, they will both display essentially the same torque-speed characteristic curves. A generalized torque-speed curve applying to both motor types is shown in Fig. 1. The predictable reactions in the two motors reveal why that is possible.

SERIES-CONNECTED DC MOTOR

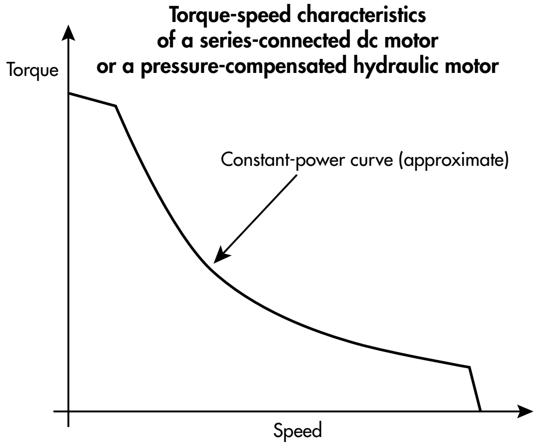
The series-connected dc electric motor *(Fig. 2)* was introduced in a previous installment of "Motion Control." At that time, it was explained as such:

"To understand the relationship between stator field magnetic flux and speed, recall that the motor will accelerate until the counter electromotive force (emf) equals (or nearly equals) the supply voltage: the battery voltage in the figure. When power is first applied, the motor shaft is not turning. Counter emf is nil, so the current jumps to a high value. The high current causes a large starting torque, so the motor accelerates. But as the motor accelerates, the counter emf increases, reducing the armature current, *IA*. The reduction in current is accompanied by a reduction in field flux. Thus, the motor now has to speed up more to generate a high counter emf, which causes a further reduction in flux, requiring yet more speed, and on and on.

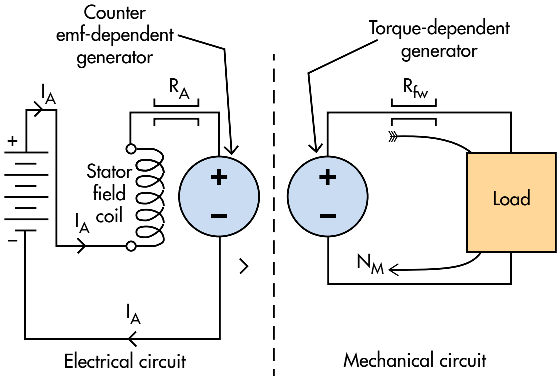
"At the same time, however, the reduced flux reduces the torque, reducing the acceleration, and on and on. In the end, an equilibrium is established wherein the motor stops accelerating at some finite armature current and some finite shaft speed.

This motor is perfectly analogous to the pressure-compensated motor whose displacement increases with increased pressure. The result is a motor with high speed at low pressure (load) and low speed at high pressure, just like the series-connected motor."

This is exactly what is shown in Fig. 1. At high speed, the



1. Series-connected dc motors share almost identical torque-speed characteristics with pressure compensated hydraulic motors.



2. In the series motor connection, the armature current is forced to pass through the stator field coil.

torque is low, and at low speed, the torque is high. The curve in Fig. 1 is often referred to as "a constant output power curve," which is not exactly true—only approximately true. An important function of the series motor is to prevent lugging of the prime mover. It does a good job of that. In the electric motor, a more significant use is as a "universal motor." In this context, universal means that the motor will operate on either alternating or direct current.

Understanding how the universal motor can function and be efficient with ac hinges on knowing that current is the causative factor for magnetic flux, and flux is what creates the operational parameter that creates the magnetic forces and thus generates the torque.

When the field winding and armature winding are connected in series, it is absolutely true that the currents in both are the same and, therefore, the fluxes and magnetic forces are always in phase. If the current is powered by one half the alternating cycle, the field and armature fluxes are attracting—that is, a north pole in the field is attracting a south pole in the armature.

When the current reverses in the next ac half cycle, it does so in both coils, and a south pole will attract a north pole, since both have changed polarity. This could not happen with the parallel field winding in the shunt-connected motor, which will not function with alternating current. It would lack the required simultaneous double, and in-phase, reversal of both fields. They would always be out of phase and by an amount that varies with the load on the shaft, leading to inefficiency at best.

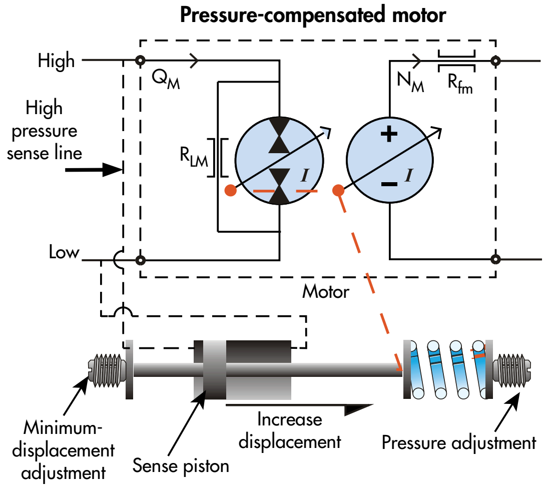
Series motors are often used on electrical hand tools such as drills and rotary saws. The high torque is desirable to get drill penetration in tough circumstances, for example, or to saw through hard knots in another, without requiring excessive and damaging input currents. Some subtle differences exist in the construction of the universal motor in comparison to a purely dc configuration. For example, both the armature and the stator iron cores must be laminated to reduce the effects of eddy-current heating and inefficiency.

One important consideration in the series motor is that speed can become excessive when the load is removed from the shaft. With lower load, the speed rises, causing the motor to increase its speed to maintain the counter emf due to decreasing current and flux. This causes the speed to accelerate further, which reduces the current even more and in turn requires further speed increases due to lessening flux.

And so it goes in an endless positive feedback situation; ultimately, the speed can run away and destroy the motor. Special features have to be incorporated in the design to prevent excessive speed.

PRESSURE-COMPENSATED HYDRAULIC MOTOR

An important goal of the pressure-compensated motor is to have low torque at high speed and vice versa, as is the case with the series-connected dc motor. The torque-speed curve for the hydraulic motor will be very similar to that shown in Fig. 1. By following the connections of the pressure-compensated hydraulic motor in *Figure 3*, it can be seen that the simplified compensation mechanism is a sensing piston with an adjustable bias spring. The motion of the sensing piston is mechanically coupled to the displacement mechanism and changes the displacement. The sensing piston cylinder is connected to the transmission pressure lines.



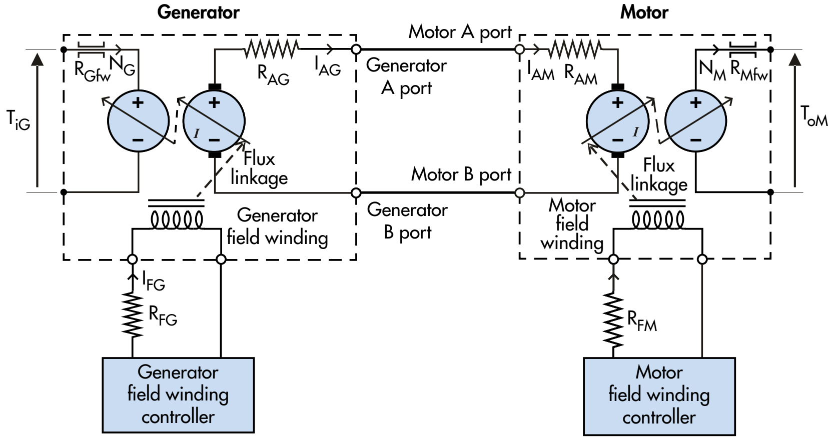
3. Combined schematic and cutaway diagram of the pressure-compensated motor; phasing is such that increased pressure increases displacement.

Note that the high-pressure side of the transmission is connected to the left side of the sensing piston, causing motion to the right. The linkage is such that the motion to the right reduces the motor's displacement, which is the desired result.

In normal operation, the hydrostatic transmission pump delivers some relatively constant flow as a result of its positive displacement pumping action. If the load on the motor is low, the transmission differential pressure will be low, causing the bias spring in the motor's compensating mechanism to force low displacement. Under this condition, the motor will be spinning at relatively high speed.

When the motor load rises, at some point, depending on how much the pressure adjustment screw has compressed the bias spring, the pressure will be high enough for the sensing piston to *lift off* its minimum displacement condition. There is, at the left side of the sensing piston assembly, a minimum displacement adjustment screw. The minimum displacement has to be set so that the motor does not over-speed at low pressure.

As the motor load torque increases, the pressure necessarily



4. The original Ward Leonard drive had controllable generator and motor field currents. The generator field current controlled motor speed and motor field current controlled its output torque. It is very similar to the hydrostatic transmission.

rises with it, further increasing the displacement. With the pump delivering a fixed amount of flow, the motor, with increased displacement, is able to absorb all of the pump's output flow, and the motor slows down. However, with the increases in pressure and displacement, the motor's torque easily rises to meet the escalating external load. The result is a torque-speed characteristic like that shown in Fig. 1.

The primary function of the hydrostatic transmission with a pressure-compensated motor is to reduce lugging of the prime mover. That is, the pump and motor in the transmission normally can carry as much as three or four times the maximum power capability from the prime mover, often a diesel engine.

The peak power capacity of the hydrostatic transmission is called the *corner* power. The compensator mechanism prevents the corner power point from ever being reached. As a result, the engine can be downsized in power capacity, but still is able to deliver high torque, albeit at low speed, as well as high speed, but at reduced torque. Meanwhile, the engine is delivering its corner power, but not being lugged. Both the pressure-compensated motor in the hydrostatic transmission and the series-connected dc motor will display this type of anti-lugging performance.

THE WARD LEONARD DRIVE

The original Ward Leonard drive *(Fig. 4)*, introduced in the 19th century, used a generator and motor with independently controllable field currents. By increasing the generator field current, the generator output voltage would rise and force the motor to accelerate until its counter-emf approached the generator voltage.

An increase in motor field current caused its counter emf to rise, and in turn slow down to match the generator output. More motor field current meant more motor flux, and thus more motor torque.

Although it was likely unimportant at the time of its patenting, the Ward Leonard drive is regenerative: If operating high inertia loads, the energy imparted to the inertia while accelerating can be returned to the electrical grid when decelerating. Furthermore, the energy flow can be bidirectional.

It is not necessary for both field windings to be controllable. It was a revolutionary idea and a very special use of electrical power. The important feature was the variable output speed. In fact, variability in output speed and torque remain important today. Here is how the Wikipedia website explains the Ward Leonard drive and its origins:

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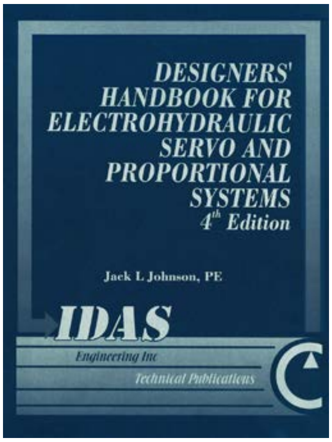
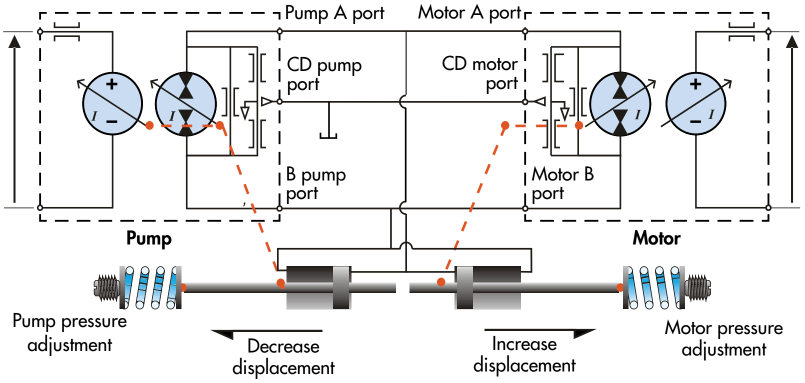
THE FOURTH EDITION of the Jack Johnson's Designers' Handbook for Electrohydraulic Servo and Proportional Systems contains a wealth of useful information describing:

- how to calculate and control pressure losses in hydraulic circuits, subplates, and manifolds,
- how to analyze and control a variety of mechanical loads, including conveyors and belts and triangulated loads,
- dynamic properties of proportional and servovalves and how to incorporate them in your system,
- practical information about electronics, especially transducers and signal conditioning, and
- mobile equipment electrical systems, including batteries and charging systems.



The 786-page Designers' Handbook contains nearly 800 pages of useful information and sells for $159. For more information or to order, visit www. *hydraulicspneumatics.com/ Bookstore-0*. Fill out the PDF order form, and e-mail of fax it to us.



5. Here is the fully functioning hydrostatic transmission, with both the pump and motor having pressure compensation.

Ward Leonard Control, also known as the Ward Leonard Drive System, was a widely used dc motor speed control system introduced by Harry Ward Leonard in 1891. In [the] early 1900s, the control system of Ward Leonard was adopted by the U.S. Navy and also used in passenger lifts of large mines. It also provided a solution to a moving sidewalk at the Paris Exposition of 1900, where many others had failed to operate properly. It was applied to railway locomotives used in World War I and was used in anti-aircraft radar systems in World War II. Because it offered smooth speed control and consistent torque, the Ward Leonard control system was widely used for elevators until thyristor drives became available in the 1980s. Many Ward Leonard control systems and variations on them remain in use.

Basic concept*—The key feature of the Ward Leonard control system is the ability to smoothly vary the speed of a dc motor, including reversing it, by controlling the field windings and hence the output voltage of a dc generator. As the speed of a dc motor is dictated by the supplied voltage, this gives simple speed control. The dc generator could be driven by any means, provided that also supplied a voltage source for the field windings. This 'prime mover' could be an ac motor, or it could be an internal combustion engine (its application to vehicles was patented by H.W. Leonard in 1903).*

The differences in the various Ward Leonard drives are primarily in the controls. The generator has been replaced by new, powerful, and flexible electronic controls, such as variable-frequency controllers. These controllers are flexible and perhaps more importantly, use ac motors. The weakness in dc-commutated motors is that the brushes undergo wear, and the brush-commutator interface is a source of arcing. On the other hand, ac motors are devoid of such nuisances. Additionally, the latest versions of ac motor controls can be regenerative and will return power to the electric grid.

The hydrostatic transmission is almost naturally regenerative. That is, a high inertial load in a stationary application will put energy back into the electrical grid. This is true of the induction motor as a prime mover as well as a synchronous motor prime mover. But neither drive can inherently provide regeneration in mobile applications. This is not a problem with the transmission; rather, it's a problem with the prime mover.

When energy is sent back into the engine, the engine is unable to convert or store the energy. Other means, such as accumulators, are required to store hydraulic energy so that it can be recovered during another portion of the machine's operating cycle.

Diesel electric locomotive propulsion systems, for example, which use modern variations of the Ward Leonard drive, require huge resistor banks. Energy is poured into these banks and converted to heat. It is no more efficient than friction brakes for deceleration. Using hydrostatic transmissions does not solve that problem unless there are accumulator storage devices.

The similarities between the hydrostatic transmission and the Ward Leonard drive are extensive and go beyond what is covered in this brief overview. The departure comes with the newer motor controls, such as variable-frequency drives for electric motors. No such advances have emerged for the hydrostatic transmission, mostly because there is no practical equivalent to the alternating-current motor or generator. It can be conceived with ac hydraulics, and no doubt has been tried, but it remains an unfulfilled dream.

To be practical, both the pump and motor in the hydrostatic transmission have to be pressure-compensated. A simplified analytical schematic is shown in *Figure 5*. For simplicity, fluid-conditioning circuits and mechanical stop limits on compensators have been omitted. The pump compensator protects the transmission from excessive pressure, while the motor compensator assures that the constant output power curve of Fig. 1 is maintained to achieve anti-lugging of the prime mover.