ELECTRICAL PRINCIPLES OF DIESEL ELECTRIC LOCOMOTIVES

Many years ago, a major league prophet of that era predicted to the people of his time that their descendants would make use of a mysterious force to light their homes, cook their food and even do many of their laborious tasks. "What is this substance, or what-have-you to be"? he was asked. "I do not know" he replied "and neither will your children's children know who will make use of it." Whereupon he was considered to be slipping badly as a prophet and relegated to a Class D team in the soothsayer's league.

He was right—we do not know what electricity is. We cannot see it or smell it or taste it—though we can feel it if we don't handle the screwdriver right when testing the spark plugs on the car. But we do know how electricity acts and can understand many electrical laws by comparing its flow with that of water.

VOLTS OR ELECTRICAL PRESSURE

For this, let us consider a couple of cases right close to home. We are going to wash the car so we get out a short length of hose, without a nozzle, and drag one end over to the faucet on the side of the house. We know there is water pressure at the faucet—the city pumping plant insures that we would find the pressure was so many pounds per square inch if we put a gauge on the pipe coming through the wall. In electricity, we also have a pressure but here it is called "voltage" and is measured as so many "volts" instead of "pounds per square inch".

Until we connect up the hose and open the faucet, no water flows—the pressure is simply forcing the water against the dead end of the faucet. Similarly, in electricity, we can have pressure or voltage without flow. For instance, when a light is turned off, the voltage is still there but the open switch blocks the flow of electricity just as the closed faucet, holds back the water.

When the hose is attached and the faucet opened, the pressure will force water through the hose. Just so will electrical pressure or voltage force current through an electrical circuit. How much this will be brings up the next subject.

ELECTRICAL VOLUME — AMPERES

If the faucet is opened wide, so that full city pressure enters the hose, a lot of water will flow. Were we to measure it, the volume of water would be expressed as so many "Gallons per Minute". In electricity, the volume of flow is measured in "Amperes".

With a full open faucet, the water flow is much heavier than we need to wash the car. So we close the faucet partially. In effect, this lowers the water pressure at the point where the hose is attached to the faucet. The water flow through the hose goes down as well. In an electrical circuit, exactly the same thing happens—if the voltage or pressure is changed, the amperes or current volume will vary in the same manner.

ELECTRICAL RESISTANCE — OHMS

So far we have considered the effect of pressure on volume of flow in the same piece of hose—or electrical circuit. Next suppose we have a chore like filling the fish pond way down at the back of the garden. We get several lengths of hose and couple them up to stretch from the house. Now when the faucet is turned on full, it will be noted that the water flow from the hose will be quite a bit less than it was through the short car-wash length. The pressure is the same in both cases with the faucet wide open. So something is holding the water back—cutting down the flow. This "something" is resistance, caused by the friction of the water against the inner surface of the hose. It is greater now because we are using a longer length of hose. Similarly in an electrical circuit, there is a resistance to flow of current when electricity passes through a wire or other conductor. The amount of this electrical resistance is measured in units known as "ohms". In an electrical circuit, the greater the resistance in ohms, the less the current in amperes if the pressure in volts remains the same.

RELATIONSHIP BETWEEN PRESSURE (VOLTS), VOLUME (AMPERES) AND RESISTANCE (OHMS)

It would be quite complicated to express a relationship between pounds per square inch pressure, gallons per minute flow and liquid flow resistance for the water flow through the hose. Here is one case, at least, where electricity is much easier to deal with.

For the relationship is that a pressure of one (1) volt will force one (1) ampere of current through a circuit whose resistance is one (1) ohm. On this is based the fundamental "OHM'S LAW" of electricity. In stating this law:

E = the electrical pressure in volts
I = the current volume in amperes
R = the circuit resistance in ohms

The equation can be written three ways, all really meaning the same thing:

$$E = IR$$

$$I = \frac{E}{R}$$

$$R = \frac{E}{I}$$

PRESSURE LOSS — "IR DROP"

Suppose we unscrew the connections at two points in our long house line and put in special couplings having pressure gauges attached. With the hose reassembled and the water turned on, the two gauges will read different pressures with the one nearest the faucet having the higher reading. The difference in readings is the loss in pressure as the water passes through the length of hose between the two couplings and represents the pressure required to force the water through that particular section of hose.

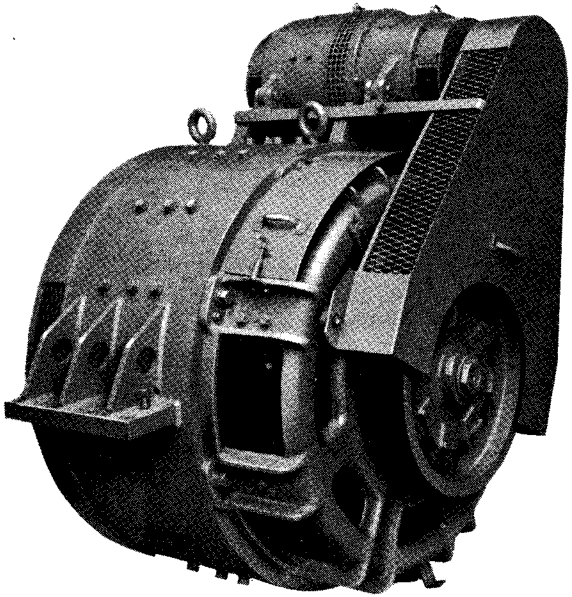
Similarly, in an electrical circuit, there is a loss of pressure or voltage in each of the various parts of the circuit. This could be called the "E drop". But $E = IR$, so the term "IR drop" is used instead because the drop is calculated by multiplying the current in amperes by the resistance in ohms. An example of "IR drop" shows up plainly if you get on a street car at night out near the end of the line. When the car starts up the lights will dim. Why? Because the current for the motors has created quite an IR drop in the trolley wire part of the circuit and so the voltage at the car is low, dimming the lights.

POWER LOSS — "I^2R" HEATING EFFECT

It required work to pump the water through the section of hose between the two couplings. Where did the work come from? From the power required to drive the pumps in the pumping station. Where does the work or energy go to—since energy cannot be destroyed, tho it may be transformed from one form to another? Here it is absorbed by friction of the water against the hose walls. Friction means heat so the pumping power actually turns into heat. Of course, the heating is not perceptible, either in the water or the hose, but it is there.

In electrical circuits, we have the same thing. It takes power to force electricity through a wire against the resistance or "friction". Electrical power is in "watts" and is volts times amperes or E x I. If we take "E" to be the voltage drop in a section of the circuit, we can call it "IR" as $E = IR$. Putting IR in the expression for power E x I, we get IR x I or I^2R. Again this "friction" becomes heat so I^2R is the heating effect. Take good note of this I^2R—it is what causes traction motors to burn out.

MAIN GENERATOR



PURPOSE

The function of the main generator is quickly stated—it simply converts the mechanical power of the diesel engine into electrical energy. Incidentally the whole main generator-traction motor combination is only a means of transmitting the engine power to the wheels. If that could be done by mechanical equipment—gears, clutches, etc.—the electrical apparatus could be eliminated. So far, however, the electrical method has proved the most practical for locomotive conditions and so it is used.

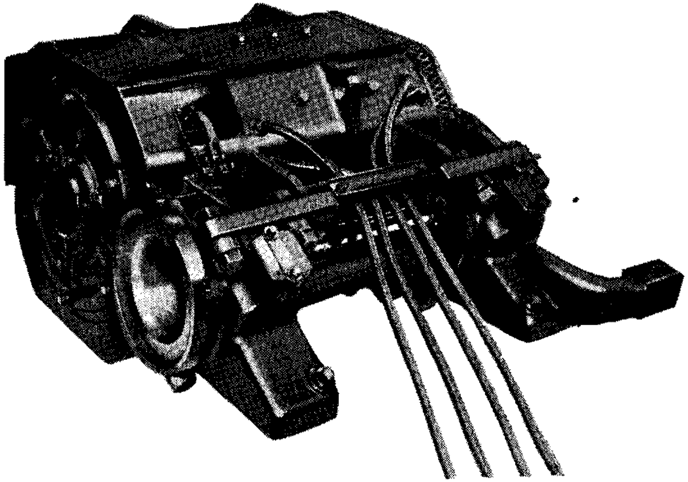
OUTPUT

At full throttle, the engine—and the generator—runs at a steady speed, no matter what the locomotive speed may be. The power output is kept approximately constant also so that the engine will operate under a steady load. If this were not done, the engine would not be putting out its full available horsepower at some times or would be overloaded at others. After all, the engine has only one job and that is to keep the generator turning over at some certain speed called for by the governor. If the power output of the main generator fell off, the engine could loaf while if the generator output went above normal, the engine would have to spit on its hands and pour in extra fuel to keep the speed up.

The matter of maintaining constant electrical output from the main generator is quite a problem due to the widely varying requirements of the traction motors at different locomotive speeds. At low speeds, on the heavy pull, heavy amperage at a comparatively low voltage is needed while at higher speeds, the voltage is high and the amperage lower. For constant output, the product of volts times amperes (power in watts) must remain the same. Unfortunately, the generators do not have exactly this characteristic. When the amperage goes down, the voltage goes up but it does not increase fast enough in the upper part of the voltage range to keep the product constant. On the other hand, when the amperage gets high, the voltage does not drop off in proportion and the product of volts times amps gets too large, tending to overload the engine.

This is where the load regulator comes into play, which is either in or connected to the governor. It is a sort of watchdog. If the engine power starts to fall off—because volts times amps are too low—the regulator says to the generator "Get busy—put out more power! The engine hasn't enough work to do!" And, to make the generator step up its output, the load regulator increases the field excitation of the generator, thereby raising the voltage (and amperage) until the output is correct. If the voltage does not fall off fast enough when the amperage goes up, the load regulator says "Whoa there! You're making the engine grunt trying to keep you up to speed!" Then the load regulator reduces the field excitation and the generator output goes down, reducing the power demand on the engine.

TRACTION MOTORS



TYPE

The diesel locomotive uses series type motors in which the current passes through the revolving armature windings and the stationary field windings in series.

CHARACTERISTICS

If a series motor is subjected to a heavy load, it will slow down. As the speed drops, the turning effort or torque will increase rapidly to take care of the drag. Obviously this is what is needed in a locomotive when the train hits a hill. Conversely, as the load lightens, the motor speed goes up. If a series motor were to be relieved of load entirely, it would turn at run-away speed and break up.

CURRENT AND TORQUE

Torque is the turning or twisting effort of the motor shaft. But, since the shaft is geared to the wheels and the wheels exert tractive effort to move the locomotive and train, tractive effort is torque in another form.

Amperage or current flow produces torque—and tractive effort. Therefore the reading of the loadmeter in the cab is high when the locomotive is starting a train or pulling up a heavy, heavy hill. Then, as the speed goes up, the loadmeter will fall back. While the loadmeter reading is a measure of the torque of the motors and the pulling power of the locomotive, a certain reading of the meter does not necessarily mean that the torque and tractive effort are always the same for that particular meter reading. The motor torque, and hence the tractive effort, will not be the same at, say, 900 amperes reading if one step of field shunting is in as it will be at 900 amperes with no field shunting connected. Also, on locomotives using the same type traction motors but with different gear ratios, the same meter readings will produce the same motor torque but different tractive effort.

VOLTAGE AND POWER REQUIREMENTS

When a train is being started, but before the locomotive starts to move, the voltage required is very low as the actual resistance of the motor windings is small—only about 0.026 ohm on a Westinghouse 370 traction motor. So, to force 1000 amperes through the motor requires only E = IR or E = 1000 x 0.026 or 26 volts. As two motors are in series, the main generator voltage is about 52. It is interesting to note that this represents 52 x 1000 or 52,000 watts of power for each motor circuit—104,000 watts for the two circuits. As 746 watts equal 1 HP, this is equivalent to about 140 HP, only a small fraction of the available engine horse power.

As soon as the wheels start to turn, the traction motors begin to generate an electrical back pressure—a voltage which opposes the voltage from the main generator. This is called the "Counter Electro-Motive Force" or "CEMF" for short. Now the main generator must put out more voltage to overcome this CEMF and force say 1000 amperes through the motor windings. Note: The figure of 1000 amps. is taken arbitrarily for example—when starting and accelerating a train, it is customary to keep the meter somewhat in the red zone which begins at a figure depending on the type of traction motor and the method of connecting the load meter.

As the locomotive speed picks up, the CEMF also increases and the voltage must be similarly built up to hold the current flow up. This is done by opening the throttle notch by notch.

Finally, when the throttle is placed in 8th notch, let us say the loadmeter moves up to 1000 again. Assuming the unit is a 1600 HP "C" Line, we have 1600 HP from the engine to the generator. One HP is equivalent to 746 watts and the generator efficiency is around 91% so the 1600 HP from the engine gives us 1600 x 746 x 0.91 or about 1,100,000 watts of main generator output. The current is 2000 amps (1000 amps in each of the two motor circuits). Watts = volts x amps or volts = watts ÷ 2000 or approximately 550 volts.

With the throttle in 8th notch, the speed continues to gain and the CEMF goes on up. Generator output stays the same—1,100,000 watts as we are at full power. More and more voltage is required to overcome the CEMF. As the product of main generator volts x amps. remains the same, the amps must go down as the volts go up. This goes on until the voltage rises to a point where something has to be done about it. Otherwise the voltage will not continue to rise fast enough to keep the generator volts x amps constant. The 1,100,000 watts output will fall off and begin unloading the engine, in spite of the load regulator which by now has gone to "full field" and has done all it can to hold up the generator voltage and output.

Before this condition occurs—when the voltage gets up to about 900 volts (on a 1600 HP "C" Line Unit) and the loadmeter reading down to approximately 600 amps—the control system will operate to introduce the first step of traction motor field shunting. A field shunt is nothing but a resistor connected in parallel with the traction motor field windings so that part of the motor current goes through the resistor instead of the motor field. The effect is just as though we had lifted up the locomotive and put in another set of traction motors with different characteristics. These "new" motors have a lower CEMF so less voltage is required to get more amperage through them. The torque (and tractive effort) is the same so there is no change in locomotive pulling power as the shunts go in. The question may be asked "why not use motors of these characteristics in the first place?" The answer is that we could, except for the fact that the shunted motors require more amperes to give the same torque. Thus either the amperage load on the main generator would have been higher—too high—to get the same train acceleration in starting or we would have to be content with slower speed pickup if we held the load meter to the 1000 amp. reading we used as an example. Rather like starting a car in high gear—it can be done but it isn't best practice.

With the field shunting in, the voltage will again rise if the speed increases. When it reaches 900 volts a second time, a further step of field shunting will go in, again reducing the voltage required from the main generator. Further increases in locomotive speed will cause third and fourth steps to be introduced. Each succeeding step is lower in resistance, diverting more of the motor current from the field windings. With the fourth step connected, the locomotive will be up to its rated maximum speed before the voltage gets too high.

When the train slows down due to grade, the field shunting steps drop out one by one. Now, however, amperage is the governing factor rather than voltage. As train speed drops under full power operation, amperage will go up. When it reaches a desired maximum, the control system eliminates the highest step of shunting which was connected when the train hit the grade. When all field shunting is out, a further drop in speed will cause the meter reading to go up and, at 1020 amperes, the motors will be at their continuous rating. At this point, the locomotive will be operating at some definite speed, which depends on gear ratio and wheel size, known as the "minmium continuous speed". The tonnage must be limited to the amount which the locomotive can handle on the ruling grade, at this minimum continuous speed. In some cases, the 1020 ampere reading can be exceeded temporarily as outlined under "MOTOR HEATING".

MOTOR HEATING

As previously described, the heating effect of electric current in passing through a conductor is I^2R. So traction motors generate heat within themselves in power operation. The heat is dissipated by radiation and by the cooling effect of the air from the traction motor blowers. With the Westinghouse 370 traction motors, a current of 1020 amperes can be carried without undue heating. That is, the blowers will hold the temperature down to a safe figure.

In some instances operation at over 1020 amps is permissible for short time intervals. Mainly this is found when starting a train where the overload period is of short duration. Also some cases are found where a grade is short and sharp so again any overload would exist for a few minutes only. Special studies are made of such situations to determine what current can be carried without raising the motor temperatures beyond a safe limit during the overload period necessary to make the grade.

The amount of heat produced in a motor is interesting to consider. At 1020 amps. and .026 ohms internal resistance, $I^2R = 27,500$ watts or about equal to the heat put out by a dozen or more electric stove burners. But heating increases as the square of the current. Thus only a 10% overload—102 extra amps. on the meter—will give over 33,000 watts heating—21% more. Thus even a comparatively small overload seriously increases the heating effect. If continued, the heating will damage the motor insulation and eventually cause a failure.

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NOTES