VOLTAGE REGULATOR, ALTERNATOR and BATTERY OPERATION
HOW IT WORKS...

By Mark Hamilton

The simple explanation is provided first, as not to leave out readers who only want a sort of overall view of how a system works, without getting too technical.

Sometimes when explaining technical concepts, it's good to use parallel comparison with a more visible and simpler working model. That is why instructors and tutorial books often use water-plumbing systems in attempt to explain various electrical occurrences. (We cannot really see volts, and amps, and ohms in wires. We use meters and other equipment to check for presence and levels of electricity, and to check up on system performance.)

In this author's many years of experience while attempting to explain functions of the alternator, voltage regulator, battery, and electrical system power consumption; *the air compressor system has been the best parallel example by far!* That may be true because most people with at least limited experience with cars will have worked around an air compressor. Quite possibly fewer people who work with cars will have knowledge of hydraulic pressure differentials and pressure loss with plumbing systems. Once again, the air compressor system will be used with attempt to explain this part of our auto electrical system.

VOLTAGE (VOLT) is a measure of electrical pressure. In the compressed air system, "PSI" (Pounds per Square Inch) is the measure of pressure.

AMPERAGE (AMP, or AMPERE) is a measure of electrical current flow. In the compressed air system cubic feet of air is the similar measure of quantity.

OHM is the measure of resistance to electrical current flow–a resistance holds back the flow of electrical current. In the compressed air system, restriction, blockage, reduced passage (metered orifice) are the terms most often used to describe the same effect that resistance will have in an electrical system.

THE COMPARISON (explanation of system functions)

The battery is an electrical storage reservoir, similar in function to the air tank for the compressed air system. (Actually, the battery does not store electricity, it would be more correct to say; "*the battery stores ingredients that can produce electricity*.") Both the battery and the air tank can store a source of energy in reserve, keeping energy available for the times we need it.

The alternator produces electrical power, which can operate devices that perform work for us. And the compressor produces the compressed air, which can be used as a source of power to operate tools or machinery.

The voltage regulator limits the maximum voltage in the electrical system. In the compressed air system the pressure regulator limits the maximum pressure. The voltage regulator will also cause the alternator to produce more output, when voltage (pressure) at the electrical system is low. And in the compressed air system, the pressure switch will turn on the compressor when system pressure gets low.

Lights, ignition, and accessories use power from the electrical system. Every time we switch an accessory ON, more power is drawn from the system. Voltage (electrical pressure) drops as power is drawn from the system, and then the voltage regulator causes the alternator to make more current. And in the compressed air system an impact wrench, blowgun, paint gun, or the fitting for filling a tire, can all use power (compressed air) from the system. When we use compressed air from the system, PSI (air pressure) drops, and the regulator turns the compressor ON. In the electrical system, the voltage regulator "turns the alternator ON," or "turns OFF the alternator" as needed to maintain voltage at the proper level. And in the air compressor system the pressure regulator stops and starts the compressor as needed to maintain the proper level of pressure.

The useful electrical system will require an alternator that can produce an *average* of more output than we use, and the regulator will limit system voltage to the safe level we need. Like most machinery, the alternator cannot stand to work at maximum output for extended periods of time. Short bursts at maximum output are okay, but normal operation will require alternator operation at only a part of full output potential, most of the time. Alternators make heat as a by-product of making electrical power, and the more power they supply the more heat they make. Some models of alternators can stand to put out a much higher percentage of their gross output rating than others, during extended periods of operation.

Air compressors have "duty cycle" ratings. The compressor also produces heat as a by-product, and if it was called upon to run continuously while maintaining high pressure, the compressor will burn out. Some models of air compressors will have a greater duty cycle than others. Expect that a hobby shop model will not be intended to run for the long time periods that a professional workshop compressor is built for.

When the electrical system needs more power than the alternator can produce, for a short time, then the battery is already connected to the system and the battery will contribute the needed power. Entering into this picture is that the alternator must spin at sufficient RPM to produce power. And there is an alternator power output/RPM curve, where available output increases with RPM. There is also a minimum and maximum for practical alternator RPM operating range. Alternator RPM is somewhat adjustable by changing the ratio of the drive pulley at the crankshaft and alternator pulley diameters. But since the engine will run slowly at times, and rev very high at other times, there is no "perfect" pulley drive ratio for all applications. The pulley drive ratio is a compromise; and what's acceptable at maximum RPM is the deciding point. (An alternator can be damaged with excessive RPM.) A pulley ratio that is good with 6,500 to 8,000 engine RPM on a circle track is far from ideal with the in-line six engine in "Grandma's grocery getter."

At low RPM, expect that early models of alternators often produced much less available output than more modern designs. And with many models of old alternators, electrical output at engine idle speed was *not* sufficient to support electrical demands. But when sitting at a stoplight, the battery could assist the alternator with support of the electrical system. And then when the light turned green we drove away with the engine spinning the alternator fast once again. The alternator soon replaced power used from the battery while sitting at the stop light, no harm done. System voltage will be low, when the alternator is not keeping up. (Voltage will be above 14 when the alternator is working, and about twelve and falling when supported by the battery.)

Drivers of old cars were accustomed to the lights dimming at idle, or the turn signals blinking slower–it was simply the result of low voltage when the alternator did not keep up. The older cars could get by with less than perfect performance. And with fewer electrical items to support, then the voltage did not drop off so quickly. The old cars also did not have electronics that would cease to operate at low voltage.

With the duration of city traffic jams in modern times, the many accessories on a modern car, and electronics that are sensitive to low voltage, of course alternator output at engine idle speed had to get better. The newer designs of alternators can produce a lot more current at low RPM, even when the gross output rating is nearly the same with the old model.

In parallel to the electrical system, with the air compressor at marginal capacity, there will be times when system pressure gets low. As when friends come over to help with a project on the weekend, all armed with air tools to operate from the small compressor in the garage. (And as with electrical systems, this didn't likely happen back in the 1960's!) The small compressor cannot support an air ratchet, an impact wrench, a blowgun, and a grinder with a cut-off wheel all at once. During those times the reservoir (tank) would have to supply power (compressed air). When average use is more than the amount produced by the compressor, then system pressure falls low.

The electrical system behaves about the same. If the average output from the alternator does not keep up with electrical system power use, then the battery falls to discharged condition, and system voltage falls below acceptable level.

The table below shows about what to expect with differences in alternators that are only one generation apart. ('60s type externally regulated compared to '70s type internally regulated. About the same test results have been observed on many occasions, when doing alternator up-grades. The same "stock" pulley drive ratio was with both types of alternators. (1969–1972, small block 350 engine, stock pulleys)

	Alternator Comparison	
	Available output at 680 RPM (Engine Idle)	Engine RPM Required for maximum available output
Externally regulated 61-amp model 10DN Delco Alternator	8 to 10amps	2400 to 2500 RPM
Internally regulated 63-amp model 10SI Delco Alternator	35 to 40amps	1275 to 1325 RPM

ALTERNATOR, VOLTAGE REGULATOR *and* BATTERY.

The alternator will generate power to operate the electrical system plus keep the battery charged. The purpose of the voltage regulator is to *regulate* the amount of power output from the alternator. (Of course! What else do regulators do? Ha!) The voltage regulator will allow the alternator to make enough power to maintain proper voltage level, but not allow system voltage to rise to a harmful level.

With regulators for the alternator system, voltage limiting is the means of controlling output. (The older "generator" systems had a voltage limiter and also a current limiter, plus a "cut-out relay" that disconnected the system when the engine stopped.) If the alternator was allowed to constantly produce all the power it could, system voltage would rise to a damaging level, the battery would overcharge, components would be damaged, and the alternator would soon overheat and burn out.

With a 100amp alternator installed, we do not drive around with the alternator constantly producing 100amps. When driving a simple car, in example a '66 Chevelle, with no accessories switched on, stock ignition, and the battery topped off with a charge, the alternator produces only about 3amps to 5amps of current! (No matter how powerful the alternator, output is limited according to system demands.)

And, in case you are wondering, the amount of horsepower used to spin the alternator changes with output. When the alternators produce only a small amount of current, the horsepower drag is very small (less than 1/3 amp). Large amount of output causes more horsepower drag (about 3 or 4 horsepower to produce 120amps output).

REGULATOR ACTIONS

Popular textbooks tell us the ideal voltage regulator setting is 14.2 volts. A range of about 14.0 to 14.6 volts is generally acceptable, and various shop manuals will typically publish about that range.

When system voltage is below the setting of the voltage regulator, then the regulator causes the alternator to produce power until voltage reaches the maximum setting of the regulator. When we first crank up the engine, battery voltage will be at about 12.5 or 12.6 volts. The regulator recognizes low voltage, and causes the alternator to produce

One more aspect of the comparison between the electrical system and the compressed air system, and that is "PRESSURE DROP" with long "lines" used for delivery. In the electrical system long lengths of wire will have resistance, amounting to a restriction of electrical power flow. And the farther down the wire we check voltage, the lower the voltage (electrical pressure) will be. Also, with increased current flow, the voltage drop (pressure drop) will increase. In example, if we attempt to operate a really powerful electrical device such as a starter, through a long, small diameter wire, then starter performance will be poor. The starter motor will attempt to draw a large amount of current through the long, small gauge wire, and voltage will be weak at the starter end of the wire. In another example, if wires from a headlight switch all the way out to the front of the car are thin in gauge size diameter, then voltage to the lights will be low resulting with dim lights.

The same can happen with compressed air systems. In younger years, there were occasions where working with air tools at low pressure was a constant irritation. Imagine an old building, with a large compressor at the far end of a long building. Back in the 1940's compressed air was mainly used to air-up tires, but not to provide service for busy mechanics wielding air ratchets and impact wrenches. The building was equipped with very old, small diameter steel tubing for the compressed air service. In that facility, the mechanic farthest away from the compressor did not receive air at full pressure. If an air ratchet or tool requiring a large volume of air was used, then the tool was down on power. Larger diameter tubing would have really improved performance of the air tools. Especially so when other mechanics closer to the compressor were using air before it gets to the end of the line.

The situation with the long, small diameter tubing, for compressed air, had the same effect as with a long small wire used to operate many powerful accessories. The accessory farthest down the wire will receive power at low voltage (pressure) level. Larger wire diameter will improve performance by delivering power at higher voltage (pressure.) Or... Use a system design providing a shorter length wire, which also will improve performance.

And now for those who enjoy the technical aspects of how things work, here is a more detailed explanation of system operation with the power. Also when driving, every time we switch an accessory ON, power is used from the system, voltage is lowered, and the regulator restores voltage by causing the alternator to make more power. This action automatically allows the alternator to provide power for the electrical system.

The system does not need as much power output from the alternator when accessories are not using power, and when the battery is fully charged. When voltage at the system rises to about 14.2 volts, the voltage regulator begins limiting alternator output. When we switch an accessory OFF, use of power from the system is less, voltage quickly rises, and then the regulator will cause the alternator to make less power.

Adjustment of alternator output, by the voltage regulator, happens so quickly that when using a meter to test the system, we see function as smooth and constant. Even the old points type mechanical regulators could open and close the points over 200 times per second! Electronic voltage regulators have replaced the old vibrating point type regulator, and electronic regulators react even faster. With a modern electronic voltage regulator, voltage at the system will be very consistent.

The battery serves as a big cushion in the system, which also smoothes out voltage level. The battery will provide momentary surges of power, which are needed when devices are switched ON. The battery also can absorb momentary excess of power in the system as devices are switched OFF. The battery prevents major and sudden voltage changes in the system.

THE METHOD USED TO ADJUST ALTERNATOR OUTPUT

The voltage regulator adjusts alternator output by controlling the amount of power it will send to the magnetic field winding in the alternator. (Alternators work through the use of magnets.) More power delivered to the magnetic field winding in the alternator will produce a stronger magnetic field, which causes the alternator to produce more power output. Alternator output is reduced when the voltage regulator delivers less power to the magnetic field winding in the alternator, as the strength of the magnetic field will be reduced.

WHY 14.2VOLTS, BUT WE CALL IT A "12 VOLT SYSTEM?

The 14.2volt level is said to be the ideal voltage level for the "12volt automotive system" because that's the amount required to fully charge a standard "twelve-volt" battery. By itself, without a battery charger, and without cables connected, a typical, fully charged "12volt" battery produces 12.6 volts. The on board charging system must exceed the 12.6 level for electrical current to flow through the battery during charging. Electrical current must flow through the battery during charging to cause chemical reaction between the liquid acid and the lead plates within the battery. The 14.2volt level causes about the correct amount of current flow through the battery to maintain a fully charged condition. Extended periods with higher than 14.2volt level will over-charge the battery (at most temperatures).

BATTERY CONSTRUCTION *and* Operating Functions

(The battery interacts with the charging system.)

There are positive and negative metal plates within the battery, each made of different materials, and with insulators between the plates. Liquid acid within the battery (sulfuric acid) is in contact with the plates, and the acid will chemically react with material at the plates to produce electrical power. When the battery is called upon to produce power, as with engine starting, the chemical reaction activity is greatly increased. When the battery is stored, very little chemical reaction takes place, however the elements are waiting in reserve and available for use at any time.

The battery must produce current for engine starting, and the battery may also be called upon to supply power at times when the alternator cannot keep up with electrical system power use. When we connect an electrical device to the battery, chemical reaction takes place to deliver electrical power. Throughout these periods when the battery must supply electrical power, the battery is being discharged.

During discharge of the battery, chemical reaction will produce electrical power. And the chemical reaction between the acid and the plates will convert material at the surface of the plates to a new compound. And as the chemical reaction changes the composition of materials in the battery during discharge, material at the positive and negative plates will eventually become the same. When sufficient material at the plates has been converted to the same material at the positive and negative plates, the assembly can no longer produce adequate power. Then the battery is considered discharged.

Chemical reaction "takes apart" existing material, and reassembles the original ingredients to form a new material. The basic "ingredients" will all still be in the new material, but after the chemical reaction has taken place, the new material will be a different compound. (It happens with manufacturing of plastics and polymers and many things that we use and enjoy.)

By applying energy to the new material, at least some chemical reactions can be reversed, and the new material will be converted back to its original form. This reverse operation is exactly what happens when "recharging" a battery. When recharging a battery, we apply electrical current (energy), in reverse direction, which will cause the chemical reaction needed to change materials in the battery back to their original form. (Back to different materials at the positive and negative plates.)

BATTERY CHARGING

With recharge, chemical reaction changes compounds at the positive and negative metal plates back to their original material. Electrical current will flow through the metal plates in reverse direction during charging, which causes a reverse chemical reaction (compared to discharge). When the battery becomes "charged," the compounds at the positive and negative plates in the battery will once again be different. With material at the plates restored back to original compounds, the battery is again able to deliver electrical power.

To recharge the battery, we apply electrical power to the battery. The amount of activity with chemical reaction during battery charging will change according to the amount of electrical current flow through the battery. With voltage at proper level, the battery will only accept the amount of current required for reasonable activity with the chemical reaction.

To little current flow will not cause enough activity with the chemical reaction to completely charge the battery. We need sufficient activity with the chemical reaction to change the compounds at the plates back to their original material. Lack of sufficient activity with the chemical reaction resulting from too little current flow may be termed as an "under-charge" condition.

The speed of activity with the chemical reaction during recharge is of great concern! The amount of activity is controlled by the amount of current flow during recharge.

Excessive current flow during battery charging may be termed an "over-charge" condition–the excessive current flow causes too much activity with the chemical reaction. The amount of activity with the chemical reaction must be precisely controlled, and the perfect charge rate is a thin line. It's a situation where too much charge rate is damaging, but with not enough current flow the battery performance will deteriorate.

It turns out that during charging, the amount of current flow through the battery can be adjusted by regulating the level of voltage as electrical power is applied to the battery. When electrical current is supplied to the battery at proper voltage level, the battery only accepts the amount of current flow it wants. And it's current flow during charging that will adjust the rate of chemical reaction activity within the battery. The operation is summed up as "charge rate."

In summary of charge rate, voltage level will adjust the amount of current flow, and the amount of current flow will affect the rate of the chemical reaction. And so with the alternator system serving as the onboard battery charger, the regulator will control voltage, and the rest will follow.

It's all quite simple, *however*, the ideal amount of charge rate will change with conditions. *(There is always something to complicate matters! Ha!)* Battery state-of-charge condition, temperature, and the duration of the charge (either long drives or short drives), are all factors that will determine the ideal charge rate. The discharged battery does not produce as much voltage as the fully charged battery. When charging a "low" battery, the discharged battery will accept a large amount of current flow, *if* power is delivered at the full 14.2volt level. Ideally, the voltage level would be slightly reduced when a battery is accepting peak amount of current during recharge. Current flow would then be optimized, which will cause the correct rate of chemical reaction. Then charge rate could remain optimized if voltage could be slightly increased as the battery regains charge. Eventually voltage must be limited as the battery becomes fully charged, and then very little current flow through the battery is required.

When primary conditions are short drives in extreme cold weather, the charge rate should be increased. Internal resistance at the battery will change with extreme cold. This and other effects of the cold will contribute to slower charge rates in cold temperatures. Short drives with a slow charge rate may not allow the battery to reach a fully charged condition in extreme cold. The ideal voltage regulator setting should be slightly higher for this type of usage.

The author has lived in cold climates, and also where it is hot much of the year. The hot weather is hard on batteries! In the hot climates, batteries typically have a much shorter life. Also expect to find more corrosion at the battery area with hot weather conditions (because the warm battery "accepts" current at a higher charge rate).

The voltage level must be precisely controlled during charging to prevent excessive current flow. Excessive current flow can damage the battery. Excessive current flow is less efficient because compounds at the surface of the plates will not have time to disperse. Also excessive amount of corrosive and very explosive gas will be produced with over-charge rates. And excessive charge rate heats the battery, which changes internal resistance of the battery.

Especially with "sealed batteries," over charging will destroy usefulness of the battery! H2O (water) is one of the compounds formed with the chemical reaction during battery charging. Many of the so-called "sealed" batteries are actually vented to surrounding atmosphere, at least one very popular model of battery has a pressure relief valve for venting. The valve allows this popular model of battery to be mounted in various positions. However, these battery are "sealed" with regard to access for adding water. When these "sealed" batteries are charged at a high rate, water and vapors will escape from the vents. And we do not have opportunity to add more water to this type of battery, when the liquid level becomes low. When we allow high rate charging, the "sealed" battery can loose liquid that we cannot replace!

Also, when charging these "sealed batteries with pressure relief valve" at a rate high enough to cause the valve to release; expect severe corrosion problems at the battery area resulting from corrosive liquid and vapors that will spew from the relief. Unfortunately, the author has seen a few cars where this unpleasant experience has occurred. (Every case was with expensive, high end, occasionally driven cars. And in every case the car was also equipped with a high output "ONE-WIRE" alternator, which was connected directly to the battery with a heavy cable.)

VOLTAGE REGULATOR LIMITING

Most important of all, when a battery reaches fully charged condition, then voltage must be precisely controlled, as forcing a charge by allowing voltage to rise above ideal level will result with all the previous mentioned problems. (That applies to all batteries.) And with extended periods of driving, all of the previous mentioned problems will happen for longer time duration. Corrosive vapors emitted from the battery during charging settle upon everything near the battery, resulting with severe corrosion at the battery area. *(And I hate when that happens with a nice Hot Rod! Ha!)*

Undercharge causes short battery life, and poor performance from the battery. During charging the chemical reaction cleans the surface of the lead plates within the battery. But insufficient charge rate (undercharging) allows a crust of lead sulfate compound to accumulate on the surface of the plates. (This happens even more so when storing batteries in a discharged condition.) The crust will block access of the acid to the active materials in the lead plates, and the crust also changes internal resistance at the battery. With too much crust build up the battery will no longer be serviceable.

It's a thin line between not enough voltage at under charge and too much voltage at overcharge. And ideal voltage level is different with various conditions. A good voltage regulator is a precisely operating piece of equipment! (And the author prefers and uses exclusively genuine Delco voltage regulators. The genuine item is more costly than some others, but it has a lot more electronics within. The Delco regulator is temperature compensating, it does an excellent job of trimming off charge rate, it has built-in back-up circuits, and voltage limiting is precise. Batteries last longer, and expect less corrosion problems when using the Delco regulators.)

"12VOLT ELECTRICAL PARTS ARE ACTUALLY 14VOLT PARTS!

With most applications, the battery likes about 14.2 volts from the alternator and voltage regulator system, when driving. Since the system must operate at about 14volts, electrical parts are designed for best performance and longest life when operating at about 14 volts. The parts can generally withstand 15volts (or more), although sometimes parts run hot or don't last as long at stress level voltages.

PERFORMANCE

Although we always aim for the best, we are always likely to loose at least a small amount of voltage with long wiring circuits. What really puts the hurt on performance is low voltage. It turns out that with voltage about 10% low, performance may be down by over 30%. Electric motors, lights, ignition coils, and various parts will all behave differently, but it's great when we connect the voltmeter with the part powered-up and running, and find about 14volts at the part.

Voltage drop at wiring will only occur during current flow, therefore testing must be done with the part connected, powered-up, and operating. In example, unplugging a wire connector at a part, and then reading voltage at the wire harness connector is not a valid test of circuit performance.

The voltage test while a system is operating is the industry standard electrical performance test. It's also very simple to do an approximate performance comparison of parts running at low voltage to parts running at full voltage, using only an ordinary car. In darkness, with the engine running and headlights ON, switch the ignition OFF while the headlights are left ON. Notice that the lights dim considerably when the engine stops, as the alternator will also be stopped and voltage drops about 10%. Or with radiator fans running, switch the ignition OFF and notice the fans slow down.

The significance of engine running and engine stopped, is that when the engine is running the alternator will have opportunity to maintain the system at about 14.2volts. But with the engine stopped the battery will deliver power at about 12volts. This simple comparison with engine running and engine stopped serves to give us a general feel for the loss of performance we can expect with parts operating at slightly low voltage. In general, voltage drop at the wiring, with delivery of power to parts, is the enemy to overcome.

THE WRENCH IN THE WORKS!

It all seems so simple just to use a quality voltage regulator built by a major company that has the overall picture all "scienced out." And install an alternator with more than enough power rating to handle all the electrical loads on the car. But in the world of automotive wiring, voltage drop resulting from long lengths of wire often prevents delivering power at full voltage level to all parts of the system. And especially with our older cars, as with favorites from the Muscle Car period, ***voltage drop in wiring is a lot worse than most people would guess***. The problem often exists with design of the system, not with age and deterioration of the wiring. It happened when these cars were new, and it happens when a new factory harness with the same original design is installed.

So if voltage throughout the system is not the same at all points, then we have a major problem with attempt to use the voltage regulator to optimize performance! The voltage drop only occurs with current flow. Large amounts of current flow through a wire will result with large amounts of voltage drop. If current flow through a wire is reduced, then resulting voltage drop will also be reduced.

If we wire the voltage regulator to read and make adjustments to the lowest part of the system, then the highest part of the system might be dangerously high. It would be safer and in better judgment to wire the voltage regulator to the highest part of the system, but then low voltage will cause poor performance at some systems, and the battery might not even charge properly.

The best option will be to work with design of the wiring layout, when making improvements to electrical systems! (The "improvements" include more powerful alternators, and modern accessories to make good use of the electrical power.)

THE BEST PLAN

The best plan for most systems is to route alternator power output to a central power distribution hub. Then send power from the hub to various parts of the electrical system, ***and wire the voltage regulator to maintain voltage at the main distribution hub***. The idea is very good, but cannot be claimed by the author as an "original." It happens that Chevy did a very good example of this design with '63 through '71 models. And the Chevy engineers did it well! It's also a system that we must be aware of when installing more powerful alternators and when installing wiring to power-up new accessories.

See more about this design and function in our Tech Section feature on "REMOTE VOLTAGE SENSING," and also in our feature on "THE CHEVY MAIN ELECTRICAL POWER DISTRIBUTION SYSTEM." Also see more about how severe voltage drop actually is with original wiring in our feature on "BRIGHTER HEADLIGHTS."