



## Direct Current and Wiring Fundamentals

Every discipline has its own spoken and written language. Carpenters speak of "cripples, jacks and studs" while illustrating their tasks with familiar shapes that describe something as yet to be. Hydraulics designers use words like "pilot valve, cylinder, and bleeder" described on paper with yet another set of symbols. We promise not to try to make you an engineer but there are a few rudimentary analytic tools and language that will help you navigate this new terrain. If you already have a working knowledge of Ohm's Law, how to calculate power consumption and read schematics and wiring diagrams, then proceed directly to Chapter 2. If you do not possess these skills, spend some time with us in this chapter and we'll tell you about it:

### The Story of Electron Behavior

A long time ago, in a galaxy not very far away there were four gentlemen named Volta, Ohm, Ampere and Watt. They aren't around any more but they left us with some tools that help us predict the behavior of some very tiny critters known as electrons. Nobody has ever seen one but we know where they are because they can be made to do some amazing and otherwise difficult tasks.

### The Force Behind the Flow

The first behavior trait is described in terms proposed by Mr. Volta. The Volt is a unit of measure that represents the PRESSURE behind a source of electrons; its generic name is "electromotive force". The Volt has been given attributes much like pressure exerted on a liquid or a gas. For example, you can have an air bottle filled to 100 PSI of air. The PSI value represents a potential for doing work. The air could be used to run a rivet gun or drill motor. If the bottle's valve is closed, there is no movement of the air in spite of the pressure and no work is being done. In the electrical world, a 12-volt battery has twice the 'pressure' behind its stored electrons as a 6-volt battery. Until you connect wires to the battery and route the energy to some location to do work then the potential energy contained in the battery stays there waiting to be used.

Voltage is measured as a difference in electromotive force between two points. Voltmeters come with probes on two test leads and you touch the probes to two points simultaneously to measure the voltage between them.

### The Flow

The next trait is measured in Amps, a unit that represents a RATE like jelly beans per day, miles per hour, and the like. An ammeter is a device that is hooked in series with a conductor supplying an electrical device with power. The term 'in series' means that you literally break the wire and insert the ammeter in the gap. In this way it can detect and display the number of electrons per second that pass through on their way to do work. If we made a comparison in the compressed air bottle analogy we would need to place a gauge in the air line to measure molecules per second of air flow.

A flow of electrons (amps) together with pressure (volts) will do work. They start engines, light lamps, spin gyro motors, run radios and do all manner of nifty tasks.

### Tight Places Along the Way

Unfortunately, there is no way to move the electrons from their source (such as an alternator or a battery) to the location where they are to do work without losing some of their energy along the way. If you hooked one mile of air hose to the 100 PSI air bottle, you would be disappointed at

Figure 1-1 Ohm's Law - Three Variations on a Theme

weighed the plate from time to time. The customer's bill was calculated from the battery plate's weight loss. Of course, the cell would require periodic refurbishment to continue its service as a gauge of energy consumption.

When the automobile industry began to emerge about 1895, many inventors assumed that electric drive would be adopted for most vehicles. From a purely technical perspective, the state of the art of components for electric cars was well advanced at this time. The DC motor, for example, had gone through a decade of improvements with the spectacular growth of the trolley industry. Indeed, most of the circuitry of the electric cars was a scaled-down version of that of the streetcars; e.g., the motor controller, to regulate speed. Lead-acid storage batteries which provided power had enjoyed fifteen years of commercial development. Unfortunately, batteries were the most expensive and recalcitrant technology on the car. Funny thing . . . even today, batteries are the biggest engineering headache in electric car design.

Early batteries, being electro-chemical, lacked the inherent durability of electro-mechanical devices. Nevertheless, fifteen years of experience demonstrated continuous improvement. Inventors in the U.S. and Europe struggled to produce small, transportable batteries for use on self-propelled streetcars. Although the battery streetcar was never successful, the technology of transport batteries received a tremendous boost. The technology advancement was transferred to the electric car and ultimately to a portable power storage medium used in automobiles for the past 87 years.

In the period 1895 to 1900, batteries for electric cars were very unreliable. The first decade of the new century brought us several developments in lead-acid battery technology. By the time C.F. Kettering's work on starter motors for Cadillac came to fruition in 1911, the foundations for aircraft DC power systems were well in place.

Batteries are assembled from individual cells having the ability to convert latent chemical energy into electrical energy. All batteries use a chemical reaction that DOES NOT occur simply because the two reactants are in close proximity. The chemical reaction inside the cell progresses when a flow of electrons occurs external to the cell's chemical system. This flow of electrons is the benefit to be realized; we can make the flow do the work. There are many forms of single use batteries. The zinc-carbon battery used in radios, flashlights and other small appliances dates back to the early 1900's. Some battery chemical systems reverse if the electron flow is reversed; the battery may be recharged. Like automobiles, airplanes also make good use of compact sources of stored, replenishable energy.

## LEAD-ACID BATTERIES

The sulfuric acid electrolyte, lead-acid battery is the most common battery used in automotive applications, both airborne and earthbound. Specialty manufacturing of these batteries for aircraft service has been going on for over 40 years. The major feature of this technology is a chemical system that utilizes plates fabricated from lead and compounds of lead submerged in a liquid electrolyte consisting of water and sulfuric acid. Stacks of plates in the cells of early lead-acid batteries were held separate from each other by thin slices of wood. Modern batteries use plastics. Modern designs for lead-acid batteries use thin sheets of Fiberglass mat that looks for all the world like a few layers of tissue.

The form of electrolyte containment in lead-acid battery has been marketed in three flavors:

- "Flooded Cell" batteries are familiar to everyone: they're still the most common battery found in automobiles. These feature loose, liquid electrolyte that can be accessed by removing a filler cap on the top of each cell. If turned upside down, they leak. After a year or so in service, they often grow patches of green fuzz around their terminals.
- "Gel-Cell" batteries have been around for decades and were the first commercially viable products that reduced the hazards and mess associated with portable lead-acid power storage. Cleaner than their sloppy cousins, they still develop green fuzz and don't perform well in cold weather.
- "Starved Electrolyte" also popularly known as "Recombinant Gas" batteries are also decades old but until recently, the RG battery has languished in relative obscurity. Consumer markets for clean, odor free power in portable power systems have mushroomed. The personal computer explosion fed the demand for super clean batteries as stored energy for uninterruptible computer power supplies.

## FLOODED CELL BATTERIES . . .

Today's flooded cell batteries are direct descendants of the batteries that whisked Great Grandma to the grocery store in odor free silence. They are strong contenders in automotive markets. In my not so humble opinion, it's sad when they're still the battery of choice for many airplanes. Flooded cell batteries routinely expel explosive gases laden with droplets of sulfuric acid. Because of the requirement to vent these gases while retaining liquids they must be constructed with

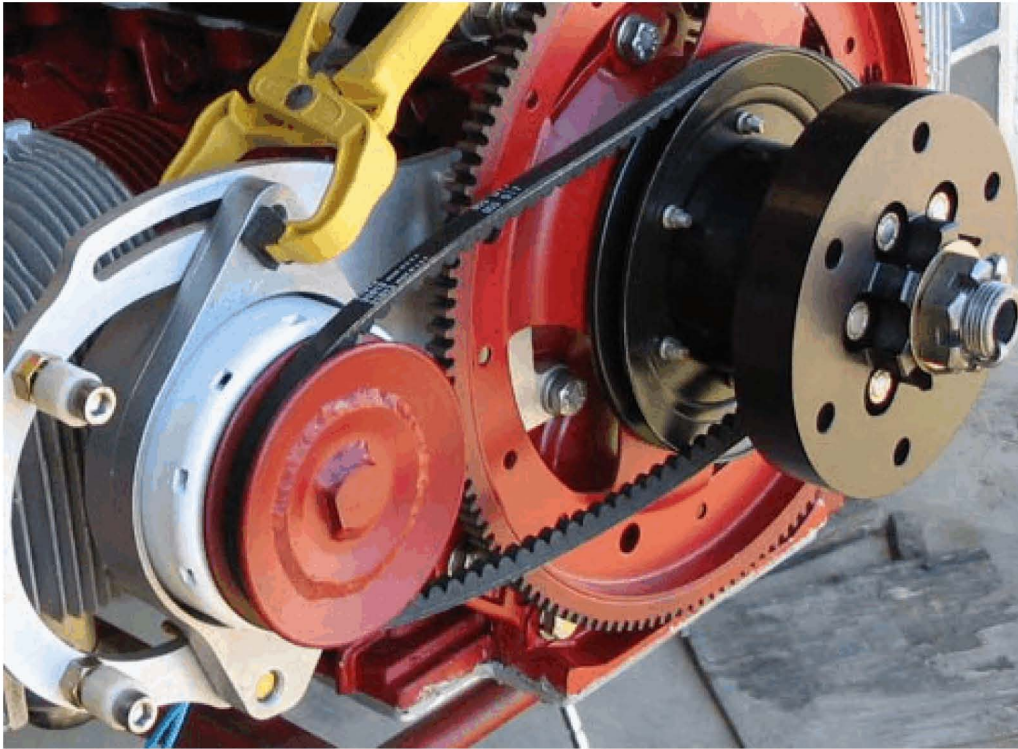


Figure 3-12. Belt Driven Adaptation of PM Alternator to Aircraft.

of failure in the alternator itself is very low. For virtually any PM powered electrical symptom, look at the wiring first, followed by the rectifier/regulator. The alternator's output voltage may be monitored for test and diagnosis with a voltmeter but remember, it is an AC voltage. In flight, the voltage from these machines may be as high as 30 volts. We'll speak to the internal workings and unique functionality rectifier/regulators for PM alternators in the next chapter.

## GENERATORS

Generators are still flying today on classic TC airplanes, on OBAM aircraft that use an engine taken from an older airplane, and several popular military trainers. If your electrical system power needs are modest and you make flights of reasonable duration so that the battery gets completely recharged in flight, there is no pressing need to replace a generator with an alternator. But they do tend to be much more troublesome than alternators.

Compare the construction of the alternator in Figure 3-2 to that of the generator in Figure 3-14. Here we find that the field assembly is the stationary part and the armature carries the power producing conductors. The current that flows in the power producing conductors of both the alternator and the generator is an alternating current. The commutator on

the generator's armature provides a sort of mechanical rectifier by tapping only the conductor that is moving through the strongest portion of the magnetic field. It also provides a means for taking power from a moving assembly. The brushes of the generator have to carry the total output current of the generator as opposed to the brushes in the alternator, which carry only a few amps of field excitation current.

The electro-mechanical switching regulator common to generator installations will be discussed in detail in the next chapter where you will see extra 'relays' used to limit output current and

prevent reverse current flow in the de-energized or non-rotating machine.



Figure 3-13 Belt Driven Generator.

Unlike alternators with self-limiting magnetics and built in rectifiers, the generator is not self limiting in its ability to produce output current nor will it automatically isolated itself from the battery if the engine stops or belt breaks.

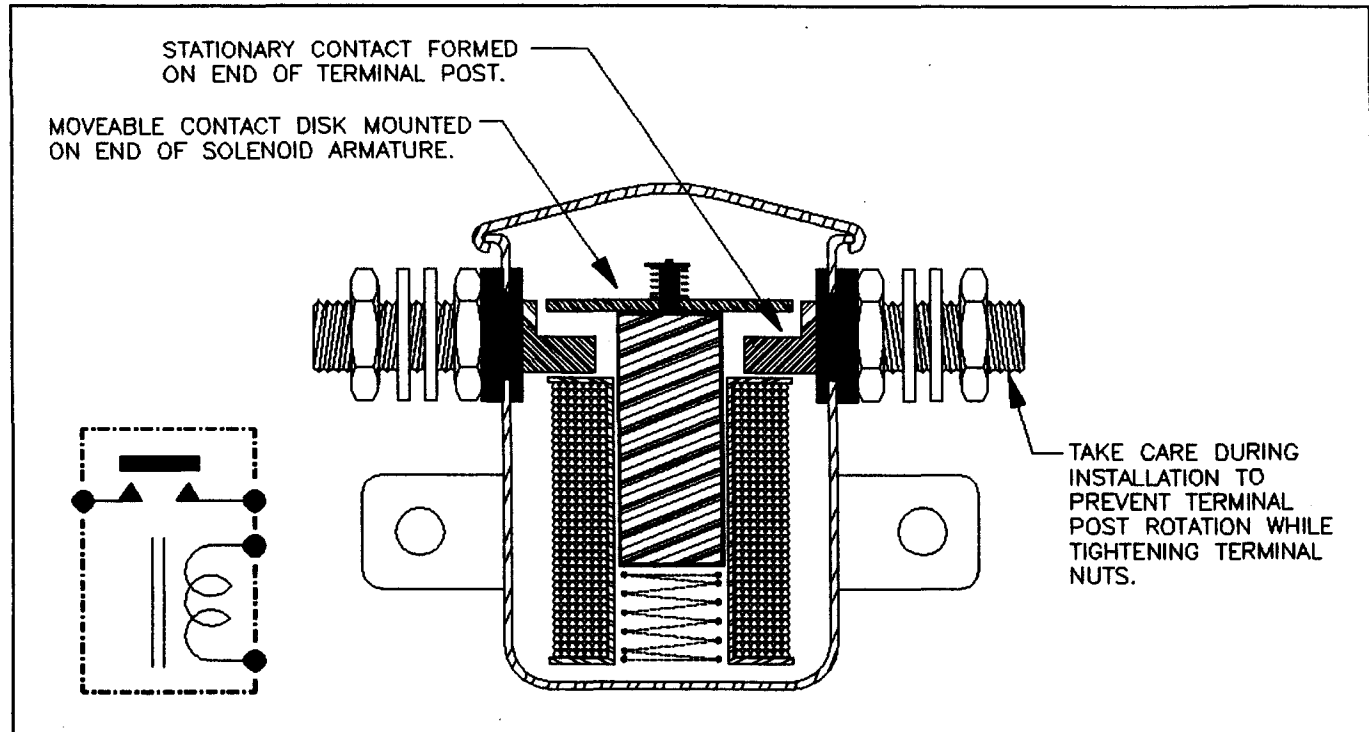


Figure 11-9. Type I Contactor Cutaway View.

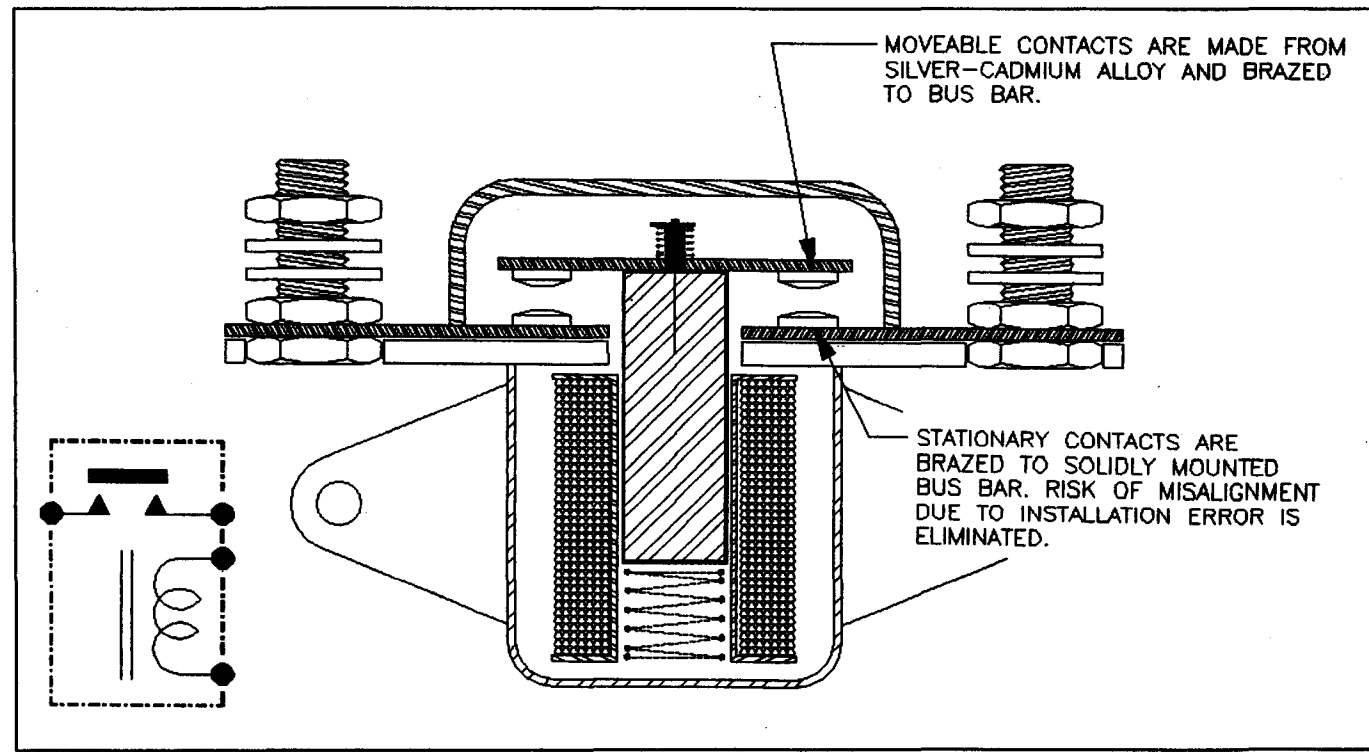


Figure 11-10. Type II Contactor Cutaway View.

tools. If you can find clean surplus parts in the Type II devices, they should be priced on the order of \$30 or less; new ones are \$160 and up. 14-volt Type II devices from surplus sources will be rare since most were originally purchased for 28-volt military vehicles.

**THINGS YOU CAN DO WITH SWITCHES**

Say what? Everybody knows that switches turn things on and off. What's the big deal? I'd agree that most of the switches we operate every day are simply a handy means of opening and closing a gap in a wire. I'll add that switches come in a variety of flavors. Aside from the simple on/off control of, say a light bulb, variations on a theme give us handy tools to simplify a variety of switching tasks.

etc.) we'll include in parentheses the dash number out of Table 11-1 which describes the switch's number of poles, number of positions and its action.

The left column of Table 11-1 is the suffix to add to the basic switch specification number. To fully describe a switch you would precede it with the standards number followed by the dash number appropriate to the action you want. For example, an S700-2-7 switch is a two pole, three position toggle switch spring loaded to center from both extremes and having an (ON)-OFF-(ON) action. The parentheses ( ) around an action label means the switch is spring loaded to leave that position when released. Other styles of switches (like rockers) will replace the "S700" with another number but the dash number to describe the number of poles: number of positions and action will remain the same.

Table 11-1. AeroElectric Connection S700-Series Toggle Switches			
Dash No.	# of Poles	# of Positions	Action Keyway - Center- Opposite
1-1	1	3	ON-OFF-ON
1-2	1	2	OFF-none-ON
1-3	1	2	ON-none-ON
1-5	1	3	(ON)-OFF-ON
1-7	1	3	(ON)-OFF-(ON)
1-8	1	2	(ON)-none-ON
2-1	2	3	ON-OFF-ON
2-2	2	2	OFF-none-ON
2-3	2	2	ON-none-ON
2-5	2	3	(ON)-OFF-ON
2-7	2	3	(ON)-OFF-(ON)
2-8	2	2	(ON)-none-ON
2-10	2	3	ON-ON-ON
2-50	2	3	(ON)-ON-ON
2-70	2	3	(ON)-ON-(ON)

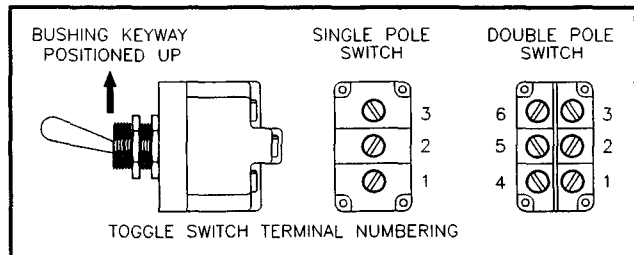


Figure 11-11. Toggle Switch Terminal Numbering.

We'll standardize all our drawings to conform to the above terminal numbering convention for switches. The mounting for a toggle switch is a 15/32" threaded bushing with a keyway cut on one side. Switch actions described in the last column have keyway side positioning of the toggle first, followed by center positioning (3-position switches only) and opposite side positioning on the right. For most applications, switches are mounted with bushing keyway oriented UP in the panel.

It is appropriate to mention here that toggle switches can be difficult to keep tightly mounted in the panel. This is because it's

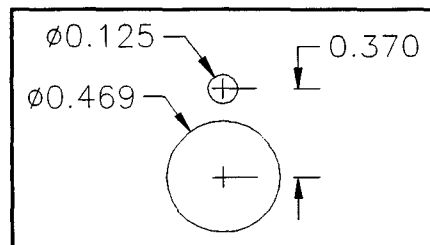


Figure 11-12. Hole Layout for S700 Series Toggle Switches.

First, I'd like to introduce you to our numbering convention. As we update schematics and power distribution diagrams, we'll try to add more detail to a switch's description. Adjacent to the reference designator number (S1, S2, S3,

because it's attached with threaded fasteners and you're always yanking on its handle. You could use thread-locker to make the nuts difficult to move after the switch is installed but this makes

waveform cycles and provides a source of energy to "fill in" the valleys between peaks. The voltage excursions experienced by the load are now much less . . . we have "filtered" some of the "noise" from the rectifier's output energy.

### **INDUCTORS . . . Make Filters Work Better Yet**

Unlike the capacitor whose major working component is an insulator, the inductor's most prominent feature is a conductor . . . a length of wire wound into a coil. Back in Chapter 7, we discussed magnetic fields which exist about any conductor carrying a flow of electrons. In that case, the magnetic field was used to do WORK . . . to drive a pointer upscale on an indicator. In the case of noise filters, we'll take advantage of the inductor's ability to store energy in its magnetic field.

In Figure 16-2, View -B- shows a series circuit consisting of an inductor (a coil of wire with a core of anything from air to very specialized magnetic materials), a series switch and a battery. The instant that the switch is closed, electrons begin to flow throughout the inductor and a magnetic field begins to build. The increasing magnetic field generates an opposing electromotive force (counter EMF) that tends to oppose the rising current in the inductor. Therefore, in the first few microseconds after the switch is closed, the current through the inductor climbs slowly at first, then increases in rate as the magnetic field becomes established. Compare the two curves in Views -A- and -B-. In the case for the capacitor series circuit, current is initially high and the rate of change (slope of line) for voltage across the capacitor is initially steep. As the capacitor becomes "charged" the current approaches zero and the rate of change for voltage also approaches zero. For the inductor, the current is initially zero and begins to increase in rate of rise some time after switch closure. The initial voltage impressed across the inductor is maximum at time of switch closure and decreases toward zero as the current in the circuit climbs and finally stabilizes at some value determined by inductance, circuit resistance and applied voltage. The charging curves for capacitors and inductors are exactly the same shape and are mirror images of each other. The characteristics of inductors and capacitors as depicted by their voltage/current curves suggest their ability to help us control noise in electrical and electronic systems.

In Figure 16-1, View -C- I show a capacitor and inductor used in combination along with the relative effects upon ripple voltage being delivered to the load. Note that

the resulting ripple voltage is still lower than that depicted in View -B-.

A physical analogy to the capacitor-inductor filter may be realized as follows: Suppose you have an innertube floating on a pond and you are able to move it by means of a long pole tied to the inner tube. Your task is to push and pull on the pole such that the innertube moves back and forth, say 2 feet peak-to-peak on the surface of the water once per second. Now, suppose a kid gets on board the innertube for a ride: the forces required to achieve the 2-foot shake will obviously go up. If you are force-limited, then for the same amount of effort, the innertube excursions will become damped as a result of having added mass to the equation. Capacitors are analogous to the innertube rider's mass.

Suppose the wooden pole is replaced with one made of rubber. Now what happens? For a 2-foot peak-to-peak excursion of your hand, the motion at the innertube will hardly give the kid a very exciting ride. Inductors are analogous to the pole's stretch. Added mass and loss of rigidity have sharply diminished your ability to displace the innertube. Suppose I said, "slow it down . . . you can take ten seconds to make the 2-foot, peak-to-peak requirement." Hmmm . . . that just might be possible in spite of the changes . . . for any given set of filtering conditions, lowering the frequency of the wiggle increases its chances of getting past any given filter. The opposite is also true, "Now move the innertube over the 2-foot interval 10 times per second." Even if your end of the pole could be moved over that distance in that period of time, I dare say motions at the other end would hardly be noticed. As the frequency of interest goes up any combination of filter components become more effective.

Filters made up from combinations of capacitors and inductor-capacitor combinations attenuate the electrical antagonists ability to "wiggle" its victim. In the case for both inductors and capacitors, the faster the rise time (slope of the wiggle waveform) the more effective the attenuation of any given filter will become. This is why small filter components can strip out the effects of VHF radio frequency interference (100 MHz = very fast wiggles) and have little or no effect on audio signals (1 KHZ . . . a whole lot slower). Larger filter components can attenuate alternator whine (1 KHz) and have little effect on the 14 volt DC power which carries the noise into your audio system.

**Ferrite Torroids and Beads** are often suggested potential cures for noise problems. As a general rule, they

## Electrical System Reliability

Everyone with an electrically endowed aircraft wants a "reliable" electrical system. How is this accomplished? Does certification have any benefits toward electrical system reliability? Having worked in the aerospace industry for 38+ years, I can attest to industry's quest for the holy grail embodied by the world's most "reliable" electrical system. Given the efforts of industry and government for the past 50 years, how are we doing?

The following article was shamelessly purloined from the pages of AOPA Pilot Magazine for March of 1999. There was no particular reason to pick this story - it was simply the most recent one I could recall. It's one example of perhaps hundreds of similar stories appearing in aviation journals for decades. I didn't want to interrupt the flow of the story so you'll find only footnote tags [ ] tying points in the story to later analysis. AOPA Pilot Magazine and other journals publish "Never Again" style articles with a stated goal of, "Enhanced safety by providing a forum for pilots to learn from the experiences of others." So, read carefully and observe. Afterward, we'll talk about what this story reveals.

-----  
**Sparks in the Dark**

*As an Air-LifeLine pilot, I thoroughly enjoy flying patients to and from places for medical care. On one such trip I took a 4-year-old patient and her father to the Cincinnati Municipal Lunken Field from my home base at the Manassas (Virginia) Regional Airport. Our return trip was to be a three-hour flight in a rented Cessna 172RG. The weather was 3,000 feet overcast at Lunken, dropping to about 1,000 feet at Manassas.*

*We left Lunken in the late afternoon, and it soon became dark. I adjusted the cockpit lights accordingly. As I tweaked the elevator trim wheel on one occasion, I noticed that the instrument lights got brighter for a second or two. I assumed that the brightening was caused by a loose wire's being jostled by the motion of the trim wheel. Since the cockpit light rheostats are close to the trim wheel, I ignored it.*

*The undercast was slowly rising to meet us, so I asked for a higher altitude. As I adjusted the rudder trim after the*

*climb, I again saw the lights get brighter briefly and again wrote it off to a loose wire.*

*During my last several trips I had been regularly updating what I called my escape route - where I would land if I had an emergency. I would open the Jeppesen book to the selected airport and tune in its ATIS. On this flight, I added a new twist to my planning - a handheld GPS. By keeping the cursor on the selected airport, I always knew its bearing and range. The airplane was also equipped with an IFR-capable GPS.*

*At the time of the electrical hiccups, the chosen airport was the Beneduni Airport in Clarksburg, West Virginia, which was well above minimums for ILS and GPS approaches. About 30 minutes after I first saw the lights brighten, they got bright and stayed that way. I looked down at the ammeter, which was pegged at a full charge. I turned the alternator on and off several times, hoping to clear the problem [1].*

*On the third cycle, a puff of smoke and a shower of sparks erupted from behind the panel. I turned toward Clarksburg, now about 20 miles away, started a descent, and called approach.*

*"Mayday, mayday, mayday, Lifeguard Cessna Four-Eight-Five-Seven-Victor. We have an electrical fire; we'll need a descent into Clarksburg."*

*The controller cleared me to 5,000 feet and asked if my ILS receiver was working. I intended to keep my transmissions to a minimum. After all, I might not be able to land at Clarksburg, and I wanted to keep the battery charged to power the ILS receiver [2]. He vectored me toward Clarksburg.*

*Just before we entered the clouds, another shower of sparks erupted from behind the panel, so I turned off the master switch and utilized the small flashlight hanging from a chain around my neck. I kept the airplane on a northerly heading using rudder only, because my hands were busy with the flashlight and setting up the radios for the ILS [3].*



Ampco/Wells . . . . p/n VR749  
 KEM . . . . . p/n KVR202B  
 GP . . . . . p/n VR301

Another interesting feature of this part is its appearance. I'm aware of no version of this regulator that doesn't look like the adjacent photograph.

**Note 22.** Most alternators do not run well without also having a battery on line. The infamous "split rocker" switch was developed for light aircraft in the mid 1960s when generators were being phased out in favor of the much more efficient alternator. A two-pole, split-rocker switch controlled the battery master contactor with one pole and



Note 21. Generic "Ford" Regulator

alternator field excitation with the other pole. The switch halves were mechanically interlocked such that the battery could not be turned OFF without taking the alternator OFF as well. The Z-figures always show a two-pole switch as a DC PWR MASTER, one pole for the battery contactor, a second for the alternator field supply.

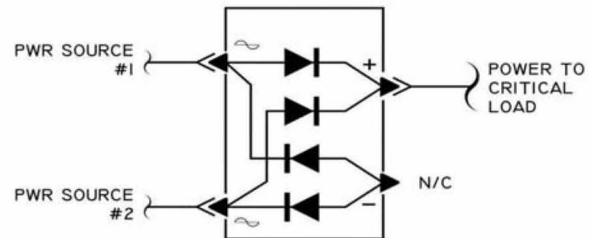
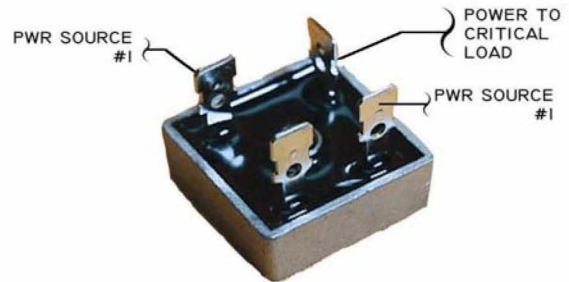
**The progressive transfer, 2-10 style switch** can emulate the popular split-rocker switch by offering an OFF-BAT-BAT+ALT function. This configuration allows battery-only ops for ground maintenance and covers in-flight situations where the pilot needs to shut down a mis-behaving alternator. See note 15.

If your system has an alternator field breaker to accommodate crowbar OV protection, **One may consider a 2-3 style switch** where the battery and alternator come ON and OFF together. This is perfectly acceptable for normal operations. In-flight shutdown of the alternator and/or battery-only ground maintenance may be conducted by pulling the alternator field breaker.

**Note 23.** Revision 11 introduces the avionics ground bus described in Chapter 18 and illustrated in the Z-figures for

the first time

**Note 24.** When you have critical loads that you would like to accommodate with dual power sources, the 4-diode bridge rectifier offers an easy to acquire, easy to mount, easy to wire solution. The figure for this note illustrates which terminals are used. Figure Z-19 shows one example of how the device is used.



NOTE 24. USING DIODE BRIDGE TO JOIN CRITICAL POWER FEEDERS

If your critical system draws more than 4 but less than 8 amps, the diode bridge should be mounted on a metallic surface for heat sinking. If the loads are heavier, say 8 amps up to the 25 or 30 amp rating of the device, perhaps a finned heat sink is called for. Consult the membership of the AeroElectric List for guidance in these special cases.

In any case, the diode bridge should be located as close as practical to the critical system's input power connection.

**Note 25. Making the SD-8 Come-Alive without a battery:** Subsequent to some excellent 'skunk werks' efforts on the part of Jim McCulley, the 'Connection is pleased to offer a work-around to older SD-8 alternator installations that encourages this useful product to come on line without benefit of a battery. Adding a pair of diodes and a start-up bias resistor as shown in Z-25, the SD-8 will come up and run as soon as the engine is started.

I've suggested the diode bridge rectifier for this application but you can use wired-leaded devices like 1N5400 series devices from Radio Shack and others. The advantage of the diode-bridge is that splices between dynamo and regulator lead wires can happen in the same PIDG terminals used to