Voltage Regulators

In this chapter we will dissect the design and application of the voltage regulators, the good and bad ones, in detail. We will discuss the history and evolution of auto and aeromotive regulators. We will talk about the current market offerings of regulators and how to best cope with their limitations. We will also discuss the future in electrical power management systems.

The output voltage of an alternator or generator tends to run up and down with engine RPM, electrical system load and to some extent inversely to the machine's temperature. Both the alternator and the generator have a 'field' winding that has one or more terminals brought outside the machine's case. By adjusting the voltage applied to the field, the machine can be controlled independently of the other effects thereby providing a means for stabilizing its output voltage. Voltage regulators, as a rule, are very simple devices and quite reliable. However, their true function and the importance of their task is not very well understood. The result of this ignorance manifests itself most strongly in poor battery life and performance.

The voltage regulator has but one purpose - to keep the battery happy. A rechargeable battery requires that the voltage applied to its terminals for proper recharging be controlled to within a few tenths of a volt. Aircraft systems designers install the lightest and smallest battery possible to do one task - start an engine. After flogging a small battery by using it to crank the engine, we compound the battery's problems by forcing it to accept a recharge at some abusive rate. The final result is to allow the bus voltage to remain at some level required to achieve 100% recharge after recharge is achieved. The excessive 'float' voltage slowly cooks the battery's innards dry.

Other problems attributable to mis-applied regulators are electrical system noise and poor voltage regulation. Damage to system components is also probable when no provisions for regulator failure protection are provided. Proper selection and application of the voltage regulator can provide real solutions to and safeguards from these problems. Voltage regulators fall into two basic categories: linear and switching. We will describe both of these types and trade off their relative advantages and disadvantages.

SWITCHING REGULATORS

The 'switcher' is the most common regulator type in both the automotive and the light aircraft worlds. Even the turbo-props use switchers on their big starter generators. Switchers are most noted for their efficiency. They operate very cool; their active electronic components can be downsized and packaged more economically than in their linear cousins.

A switcher gets its name from the fact that its major controlling component is operated much like a switch: it is either turned on or off completely with no intermediate levels of current flow allowed. An analogy to this might be to compare an instrument panel dimmer rheostat with the nav lights switch. The switch has only two positions: on and off. The rheostat has many positions ranging from fully on to completely off. A rheostat does get warm or even hot when it is set for an intermediate position, but not when it is full on (zero ohms) or when it is full off (zero amps). A switch dissipates very little power in accomplishing its task; its 'on' resistance is measured in milliohms.

With only two positions for a switch, some other attribute must be present to accomplish what appears to be the linear control of an otherwise unstable power generating device. Obviously if the switch were simply closed, the field would receive full bus voltage, the machine's output would rise, the field would get more voltage, the output would rise further and so on. The effect is a voltage runaway and much smoke may follow. On the other hand, if the switch were simply opened, there would be no output from the machine at all. The secret here is that the switch is closed for only part of the time and open for the rest. Further, the rate at which it is switched is so high (100 to 2000 times a second) that the effects of the switching are not perceptible to us or to the equipment powered by the alternator. Control of the machine is achieved by varying the "duty cycle" or on/off ratio of the switch.

To illustrate this concept , let us suppose that we have a 5-volt lamp attached through a switch to a 15-volt battery. If you simply close the switch, the lamp would burn very brightly for a short period of time before succumbing to the over-voltage. However, if you could arrange a device to open and close the switch 100 times

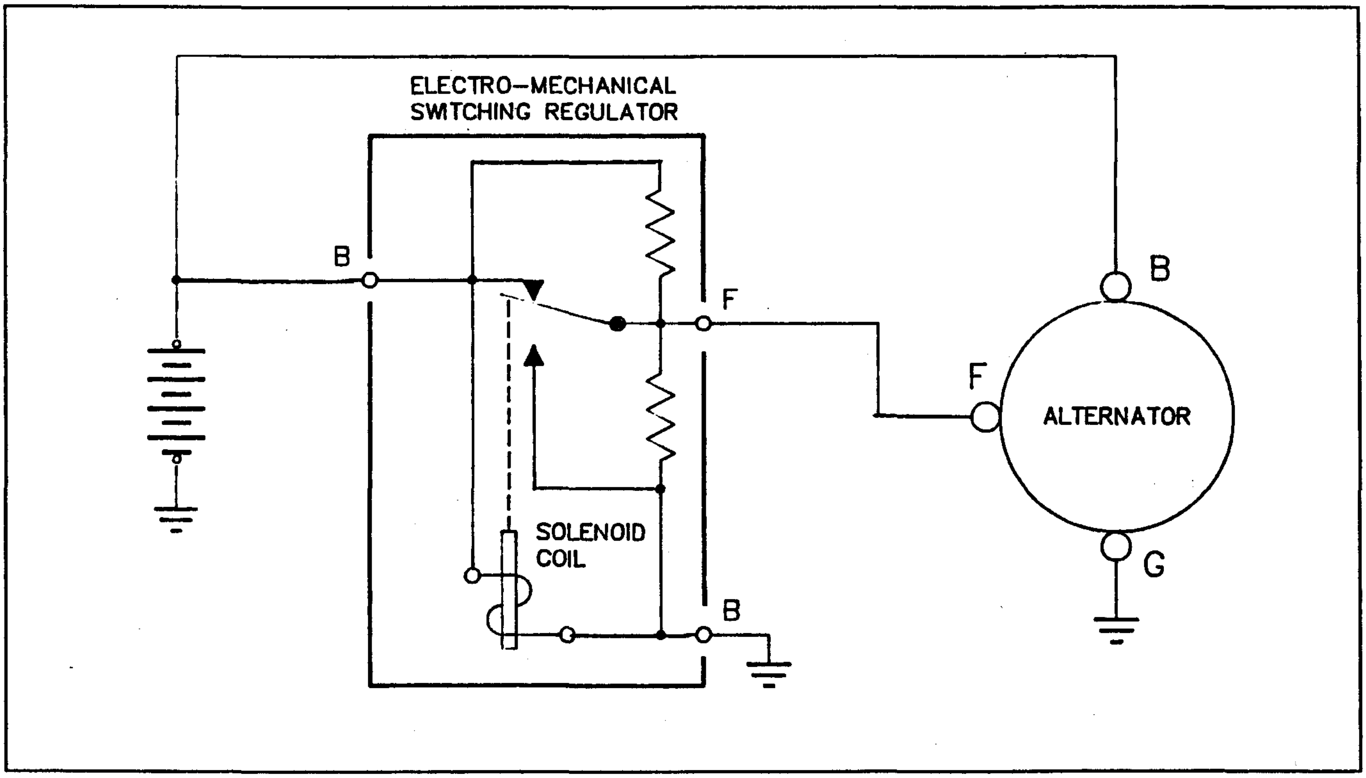

Figure 4-1. Electro-Mechanical Switching Regulator

per second and further, if the on/off ratio could be continuously adjusted so that the switch was closed for a short portion of that 100th of a second and open for the longer portion, then the AVERAGE POWER applied to the lamp could be set to illuminate the lamp at its normal intensity.

This could be accomplished in spite of the fact that a full 15 volts is applied to the lamp all the time the switch is closed. The power lost in the switch would be quite small; there is no voltage dropped across it while closed. When open, there is no current through it. If the switch were operated at 10 times per second we might well expect to perceive flickering in the lamp. However, at 100 times per second no flicker is visible due to the thermal inertia of the lamp's filament and the visual retentivity of the eye. Indeed, the common household lamp is operated from a current that goes to zero, reverses in polarity and goes to zero again 120 times per second with no visible flicker. The trick in the switching regulator is to design circuitry that accomplishes a variable duty cycle control of the switching transistor, which in turn controls the field winding of the machine.

Before the transistor, alternator and generator regulators utilized a device that looked somewhat like a relay. This was a special relay that was normally closed so that full field voltage was available to the machine. The concept is illustrated in Figure 4-1. The generator's output voltage was applied to the coil of the relay. As the voltage rose, the upper contacts of the relay would just open, at say 13.8 volts, and reduce excitation to the field. The output voltage would then fall and the relay would reclose. The resistors shown caused a reduced amount of field voltage to be applied when the upper set of contacts parted. Under very light load conditions or with high engine RPMs even the reduced excitation to the field was too high thus allowing voltage to rise further. At a somewhat higher set point, say 14.0 volts, the relay armature would be pulled harder until the lower set of contacts would close. This would result in a dead short being placed across the field, killing the output completely.

The net result of this operation was a short buzzing action wherein the contacts would be constantly opening and reclosing at some rather high rate. The on/off ratio would change depending on the machine's RPM and load. The normally closed contacts would be in

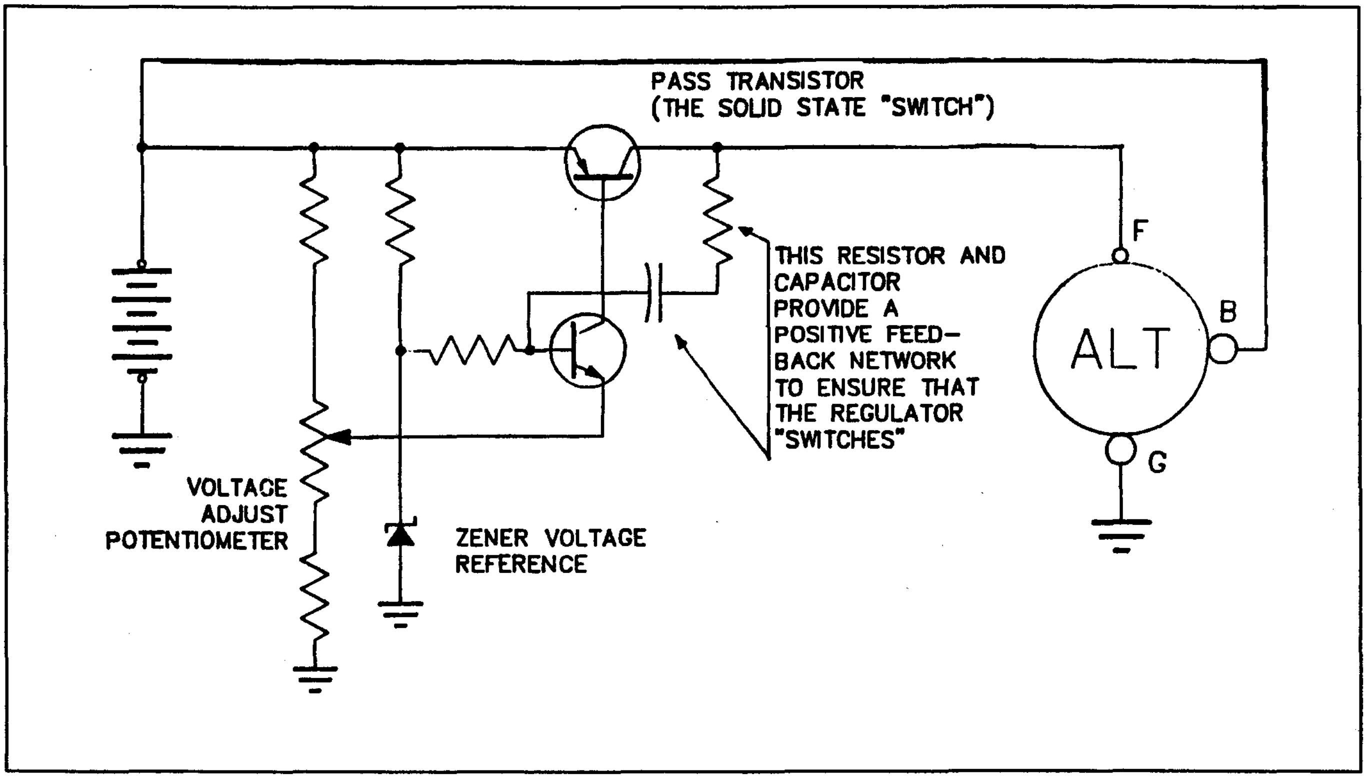

Figure 4-2. Solid State Switching Regulator.

volved in the low RPM, high load scenario; the normally open contacts would take over in the high RPM, low load situation.

A battery's ideal charging voltage is temperature dependent, so a temperature sensing bi-metal spring was usually included in the tension setting system of the relay. As it got colder, the tension increased and raised the voltage control setting. At higher temperatures, the tension was decreased with a corresponding decrease in voltage setting. This deceptively simple mechanism had a lot of clever designing behind it; aside from mechanical wear limitations and tricky calibration it performed rather well.

The availability of transistors made it possible to build a no-moving-parts switching regulator that was not subject to mechanical wear and dirty contacts. However, transistors are not without their weaknesses. Voltage spikes from other devices in the system can cause them to fail. They must be protected from their own internally generated high temperatures. Further, they require additional devices to make up the total circuit which tells them when to turn on and off. Temperature sensing must be accomplished with another kind of device than a bi-metal spring. Figure 4-2 illustrates the schematic for a simple, solid state switching regulator.

Calibration of the solid state regulator is easier: a small adjusting potentiometer is included for this purpose. Temperature compensation is accomplished with a 'thermistor' (a kind of temperature dependent resistor). A solid state voltage reference device known as a zener (zee-nur) is used as a standard of comparison. As the bus voltage rises, transistor Q1 tends to shut off, which in turn shuts off Q2. Field voltage to the alternator is reduced which brings the bus voltage down. A network of components provide a positive feedback network that speeds up the transitions from on to off, reinforcing the switching action. The output of a pass transistor in a switcher is a train of variable duty cycle pulses.

It is possible to buy a complete switching regulator as an integrated circuit complete with temperature sensing. Most modern automobiles use very compact solid state switching regulators that are built right into the rear endbell of the alternator. They have achieved a high degree of reliability at very modest costs. We visited an automated assembly plant for automotive

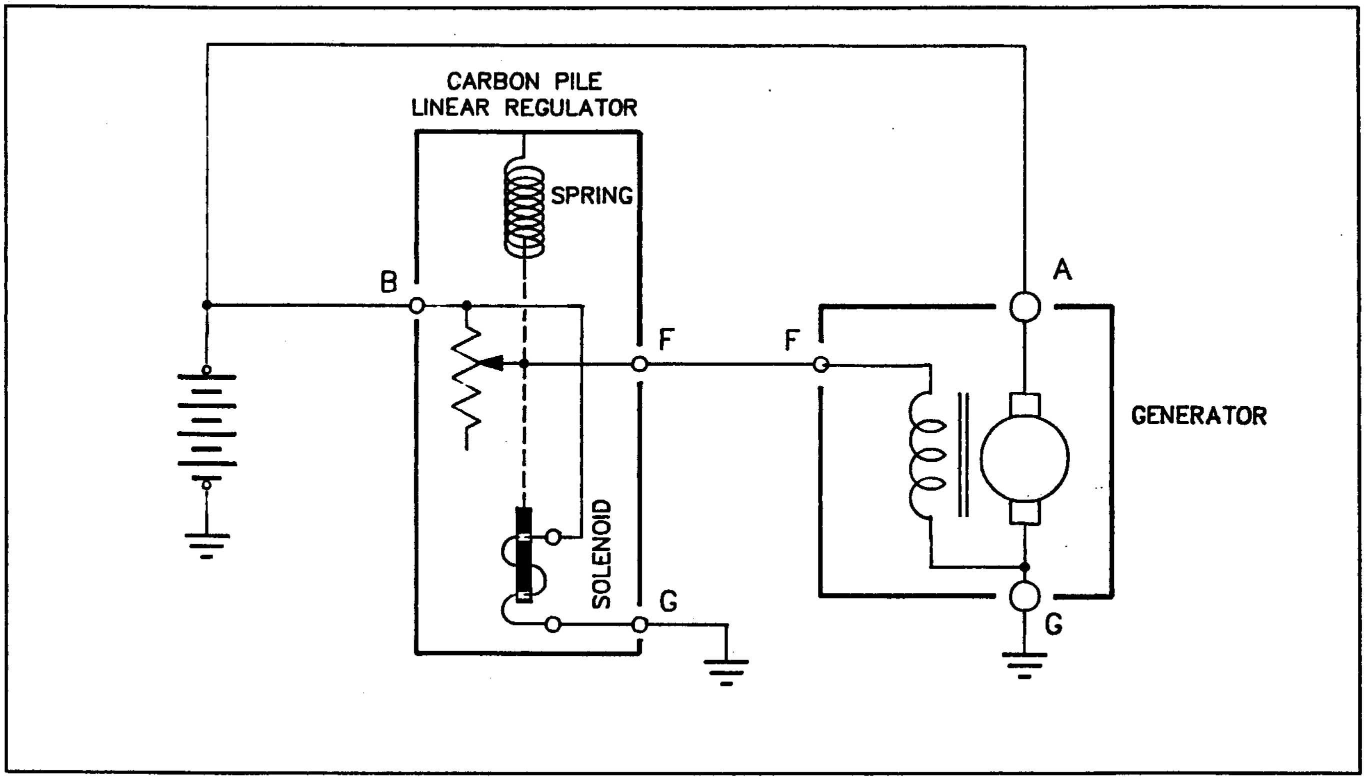

Figure 4-3. Electro-Mechanical Linear Regulator

voltage regulators in Fon du Lac during Oshkosh '86. Their out-the-door price for a very sophisticated switching regulator was less than a dollar (in lots of 100,000!).

LINEAR REGULATORS

The linear regulator controls the field winding of the alternator with a close equivalent of a smoothly adjusted DC voltage. The operation of a linear regulator could be approximated by connecting a rheostat (variable resistor) in series with the field winding of an alternator. In order to maintain the desired output, a voltmeter could be used to help adjust the rheostat.

The linear regulator has its counterpart in antiquity too. One of the best regulators available in the late 30's and through the 40's was a device known as a carbon pile regulator; its principle is shown in Figure 4-3.

The 'pile' was a stack of thick carbon washers or disks with conductors attached to each end of the stack. The resistance to the flow of current throughout this stack was a function of the mechanical pressure applied to the stack of disks. There was little or no motion involved in varying the pressure on the stack. A spring was used to keep a constant pressure on the stack (hence a low resistance in series with the field) when the bus voltage was low. A solenoid was rigged to relieve the pressure (thereby raising the resistance in series with the field) as the voltage in the solenoid was increased. By careful design of the spring, solenoid and carbon pile, a very effective voltage regulator could be built.

Very sophisticated carbon pile regulators were developed, capable of pairing two generators such that they would share the load on a twin engined aircraft. One feature of the carbon pile device is still present in the modern solid state linear regulator: the controlling device gets a lot hotter than the one used in a switcher. If you ever come across an old regulator in a surplus store, it can be easily recognized by its cylindrical, cooling finned housing - about 2.5" in diameter and 5" long. You might be interested in buying it if you can get it cheap; it is a true antique.

The controlling device in a linear regulator is also a transistor like that used in the switcher, the difference

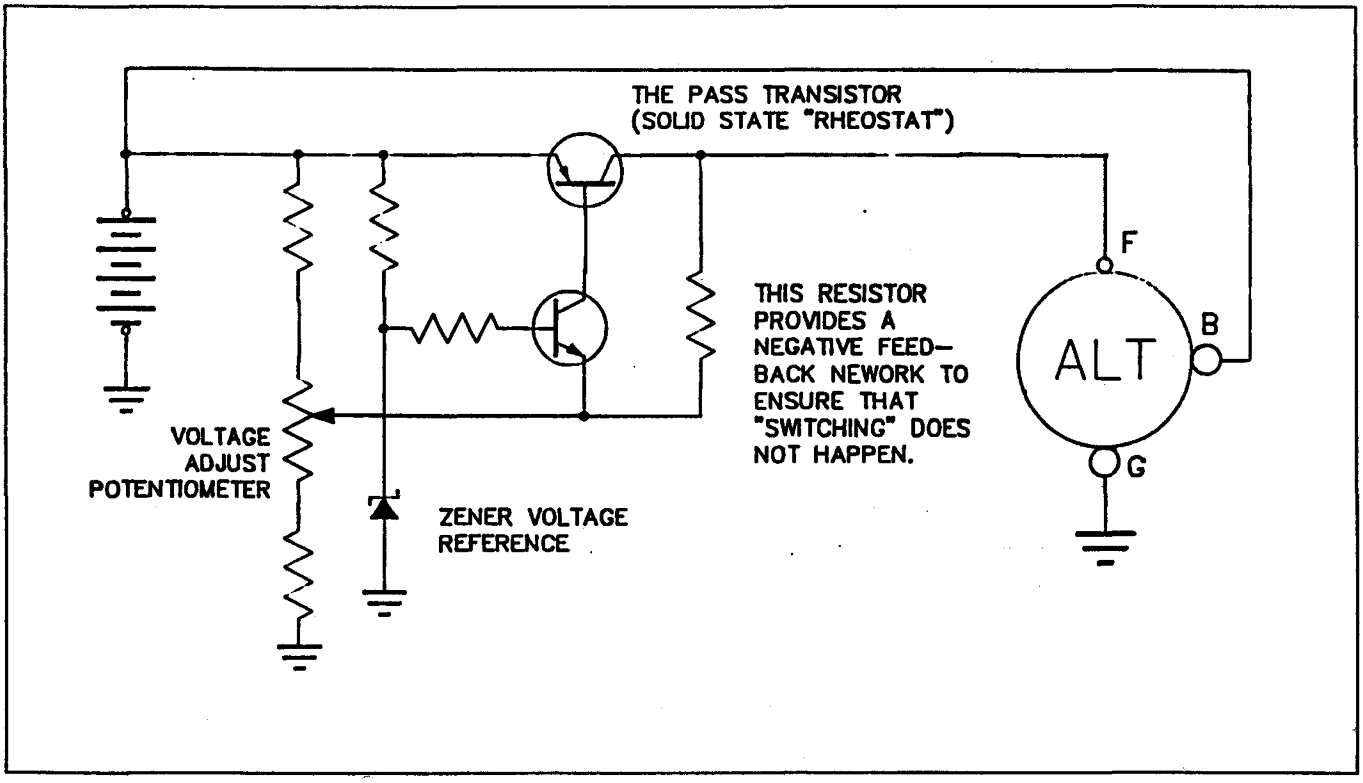

Figure 4-4. Solid State Linear Regulator

being in the manner they are driven by their associated voltage reference and comparitor circuits. The major difference between the two circuits is in the 'feedback' network. In the switcher a positive feedback network is used to increase transition speed between on-off and off-on. In the linear, a negative feedback network reduces the gain and speed of the circuit to ensure that switching does not occur. The drive to the linear pass transistor is a variable DC current designed to sneak up on and smoothly intercept the desired output voltage from the alternator. The circuit shown in Figure 4-4 is a simplified linear regulator. Not much different from the switcher shown in Figure 4-2, but very different in the way it performs.

SPECIAL REGULATORS

Some engine driven power sources flying on homebuilts today utilize permanent magnets instead of externally excited fields. The output voltage of these machines is proportional to engine speed and requires a special type of switching regulator to mate them to the electrical system. One example of this type of system is the small 'dynamos' sold by B & C Specialty Products. Incidentally, someone who had picked up a flier on the Aero-Electric Connection at Oshkosh '87 sent me a request in the mail asking about these devices. Since I did not design the particular regulator that Bill uses, I will have to do some research and provide an update to these pages with the next issue.

TO SWITCH OR NOT TO SWITCH . . . .

The major reason for selecting a linear regulator over a switching regulator has to do with electrical noise. Have you ever tried to listen to an AM radio while using an old electric razor? Most of the old razors used a simple pulsed motor that was commutated by a pair of contacts that opened and closed their very inductive windings many times per second; lots of arcing too! They stood high on the list of electrical noise generators; second only to an arc welder! The 'relay' type voltage regulators also suffered from the arcing contact syndrome. Careful selection of materials and associated components was able to reduce the noise from these devices to tolerable levels.

Solid state switchers certainly do not suffer from arcing contacts - there are no contacts. However, they do generate square wave voltage waveforms. An irrefutable law of physics states that a square wave signal contains harmonic energy that extends many octaves above the basic switching frequency. This energy can cause degraded performance in low frequency radios such as ADF and Loran-C, and in audio systems.

This harmonic energy is a function of the speed with which the pass transistor can be made to switch. The faster the switching speed, the cooler the transistor operates, but it generates more noise. If you slow down the transitions of the drive signal to the pass transistor in favor of the radios, the hotter it becomes. Slow it down enough and (1) the output doesn't switch at all, (2) the radio noise goes to zero, (3) heat dissipation becomes an issue and (4) you now have a linear regulator!

Switching regulators are found on virtually all production airplanes. Their predominately metal construction provides the best possible environment for isolating the radios from the regulator noise. The widespread use of composites in homebuilts presents a different picture. Shielding of radiated electrical noise and filtering of conducted noise is much more difficult. Further, antenna systems on plastic airplanes tend to suffer in efficiency (more on that in the chapter on antennas) making it more important to design the electrical environment for the best possible noise reduction. The linear regulator's only bad trait, liberating some heat, can be dealt with by reasonable heat sinking of the pass transistor.

THE ULTIMATE REGULATOR

Unfortunately, it does not yet exist but we are working out several approaches to the design. The major features of the regulator will include: (1) a remote temperature sensor that tells the regulator what the present battery temperature is, (2) a battery charging current sensor that adjusts the alternator voltage to produce a constant current charge until the battery is fully charged, followed by (3) a voltage reduction to the proper battery sustaining level after full charge is achieved.

The regulator will undoubtedly be packaged together with an appropriate over-voltage sensor and automatic shut-down circuit as well as an under-voltage warning light driver. We might also include a LED bar graph driver to indicate present bus voltage, alternator current and battery current.

HOW REGULATORS FAIL

The voltage regulator can fail in several ways. The most common failure is to simply drift out of calibration so that the battery is no longer properly cared for. If you are fortunate, the regulator is adjustable and can be recalibrated. However, if an adjustable regulator needs calibration for the first time in many hours of otherwise proper operation, watch for a continuing trend. The component or components that were once stable may be heading south and it is not unusual for the pace to pick up. Less expensive, high volume production switchers are seldom adjustable and must be replaced when they drift out of calibration.

A second failure mode is for the device to simply roll over dead and kill the output of the alternator completely. This is the more benign total failure mode.

The third mode is a thriller. Something breaks or shorts causing the full bus voltage to be applied to the field of the alternator. The output of the alternator rises as fast and as far as the things tied to the bus will allow. Batteries put up a valiant effort to absorb the excess electrons but they eventually succumb. Everything else takes it where it hurts - in the pocketbook. Insult is added to injury when you find yourself airborne at night (or worse), the lights go out and the radios make strange noises before going dead. If the situation really gets going, maybe the boiling battery will fill the cockpit with a terrible tasting fog. Forgive my melodramatic description of this unhappy event. It's the nicest way I can think of to talk about it.

Do the spouse and kids a favor (your life insurance company will appreciate it too!),
install an over-voltage relay between the bus and your voltage regulator. 'Nuf said on this for now; see chapter 6, Power System Monitoring, in the next issue.

SELECTING A REGULATOR FOR YOUR AIRPLANE

First, if you do not plan to have radios, then by all means install a switcher. If you plan only vhf radios, a linear regulator might be of limited usefulness in reducing noise in the audio system. If you have plans for an ADF or Loran-C receiver in a metal airplane, I would strongly suggest using a linear regulator. If your airplane is composite . . . . . . well, we supplied the regulators for Voyager. We would not have considered anything but a linear regulator for that application.

WHERE TO FIND A REGULATOR

If you can live with a switcher and are willing to tolerate battery abuse that is no worse than that which occurs in your automobile, then the auto supply stores are good sources. Airparts distributors may be able to supply regulators packaged with over-voltage protection and under-voltage warning equipment. You may find some alternators with built in regulators attractive. Many of these are suited to aircraft installations with some exceptions. See the chapter on Engine Driven Power Sources in this issue and Power System Monitors in the next issue.

Some replacement regulators for early automotive alternators look like the big black box full of 'relays' that they replace. (Check on a regulator for about a '72 Chevrolet.) They may in fact be solid state equivalents and should be considered. They are light for their size and very inexpensive. Further, most automobile regulators are temperature compensated to lead-acid battery charging curves. In any case, do not pay the extra bucks to buy a switcher used on a certified production aircraft. Except for the types used on heavy twins, they are generally no better than automotive in both parts and workmanship.

I know of no sources for linear regulators outside the aircraft parts community. Inquiries to dealers of surplus aircraft parts may locate reasonably priced linears. One brand name that is fairly common is the Lamar. Be sure the offering is indeed a linear; many companies build both linears and switchers in similar packages. B & C Specialty Products is the only company I am aware of that builds a linear for single engine airplanes and combines it with all the necessary protective and warning circuitry in one package. It is the regulator we designed specifically for the Voyager.

INSTALLATION

Temperature compensated regulators are best for keeping the battery happy. If the presence of temperature compensation is unknown, cool the regulator with a piece of ice (dry ice or a small CO2 extinguisher works well too) while running the engine and watching the bus voltage with a precision voltmeter. If the voltage goes up as the regulator case cools, it is probably compensated. If the voltage goes down, consider having the temperature compensation checked in a more accurate environmental test. A regulator with a positive temperature coefficient could be very hard on your battery.

Most production regulators I have encountered in the general aviation environment were designed to be stable with temperature. I suppose the airframe manufacturers reasoned that since they were not going to mount the regulators on the battery box it would be better to have no compensation at all.

If your regulator proves to be compensated, then you should make every effort to mount the regulator close to the battery so that they share a similar temperature environment. If the regulator is not compensated and designed to be stable with temperature, then location with respect to the battery is not important. Hot environments are to be avoided, especially if the regulator is a linear.

Poor wiring practice can cause the regulator to sense a voltage at its input terminals that is quite different from the voltage at the battery terminals. This is because wires are not available yet with zero ohms resistance. A few milliohms here, a few milliohms there and a couple of amps can make a few hundred millivolts difference. It might not seem like much but then you aren't a battery.

The problem is most common in a composite airplane. Figure 4-5 illustrates a wiring technique that minimizes these errors by running a separate ground and voltage sense wire for the regulator directly to the battery. In a metal airplane, a local ground to airframe will suffice but it is still a good idea to take the sense wire directly to the battery.

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* CAUTION *

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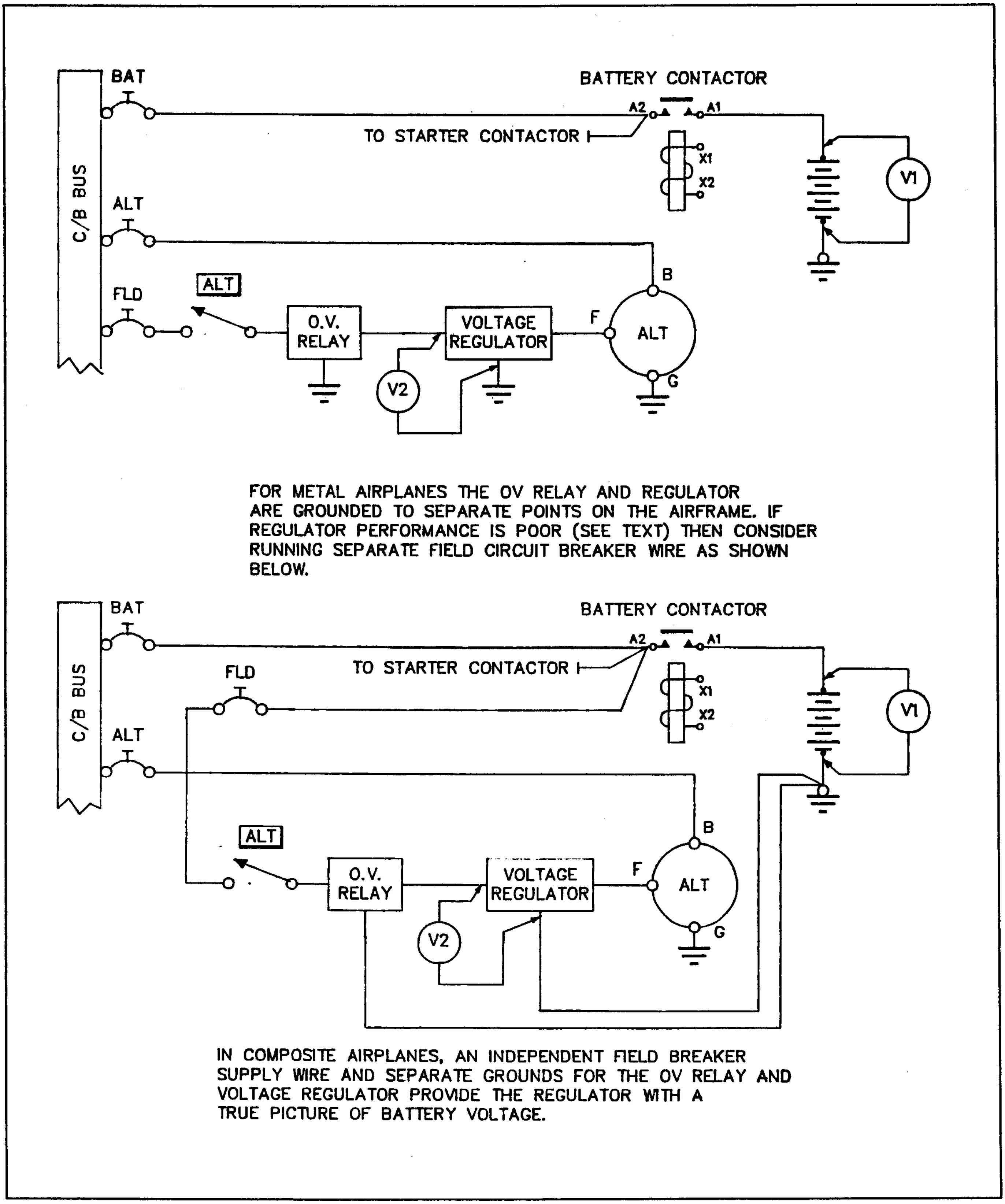
When deprived of a ground, some regulators will run away and cause severe over-voltage conditions to occur. Check the regulator you choose for this condition and be sure that your over- voltage relay is working and enjoys its own ground. Simulate the failure on the ground, radios off, so that what might happen in flight is no surprise.

IS THE REGULATOR DOING ITS JOB?

Just because a regulator is marked as having been set at 13.8 volts doesn't mean that it is still regulating at 13.8 volts. If a mediocre grade of components was used in the assembly of the regulator, its setpoint may



FOR METAL AIRPLANES THE OV RELAY AND REGULATOR ARE GROUNDED TO SEPARATE POINTS ON THE AIRFRAME. IF REGULATOR PERFORMANCE IS POOR (SEE TEXT) THEN CONSIDER RUNNING SEPARATE FIELD CIRCUIT BREAKER WIRE AS SHOWN BELOW.

IN COMPOSITE AIRPLANES, AN INDEPENDENT FIELD BREAKER SUPPLY WIRE AND SEPARATE GROUNDS FOR THE OV RELAY AND VOLTAGE REGULATOR PROVIDE THE REGULATOR WITH A TRUE PICTURE OF BATTERY VOLTAGE.

Figure 4-5. Regulator Performance Testing.

drift with time. Installation can also affect how well a regulator functions. You may have heard of the dreaded 'ground loop'. These lurking demons are responsible for many a failed or malfunctioning component or system. We'll talk about grounding in detail in Chapter 5 but we will cover grounding of the regulator here as a specific case.

Recall that a regulator is interested in the voltage presented to the battery. Further, we have seen that while the effects of resistance of wires can be minimized, it can never be zero and should be a consideration in critical cases. Figure 4-5 shows where voltages need to be measured and compared to determine if 1) the regulator is adjusted properly and 2) if the regulator is truly sampling the voltage seen by the battery. The voltmeter used to make these measurements must be capable of measuring your system voltages to the nearest 0.01 volts. We will measure the voltage at the regulator's input terminals and at the battery terminals while in flight. You may have to make temporary installations of some long lead wires to extend the voltmeter's reach during these tests. Incidentally, when we show a voltmeter probe as sampling some point close to a piece of equipment, the implication is that you must extend both leads of the voltmeter as needed to sample as close to the device depicted as possible. It is not sufficient to 'ground' one lead of the voltmeter and then probe with the (+) lead only.

First, determine what the temperature of the battery will be during this test. Plus or minus 10 degrees F is close enough; we just need to find the ballpark between a Minnesota winter and a Phoenix summer. While in flight and after the battery has had time to recharge, make voltage readings shown with your normal VFR-day electrical loads on, then again with VFR-night loads. Then if you have any heavy drain items like pitot heat or electric cabin heat, make a second set of readings with all of these devices on too.

Temporary loads such as landing lights, flap motors, and landing gear motors should not be on for these measurements. We are concerned only with flight conditions which are relatively static and occur for hours at a time. You may wish to turn these devices on and observe their effects; any large shifts, say +/- 0.5 volts or more, may indicate some inadequate feature of the system wiring. However, such excursions of voltage are not relevant to this investigation.

Back on the ground, go into the chart in Chapter 2 for battery temperature verses charging voltage per cell. Multiply by the number of cells in your battery: 6 for a 12-volt and 12 for a 24-volt.

Compare the regulator voltage readings (V2) with this figure. If there is more than a 0.15 volt departure from the ideal voltage for a 14-volt system or 0.3 volts from the ideal for a 28-volt system, I would recommend readjusting your regulator. If you find that your regulator is adjustable but not compensated for temperature, consider readjusting the regulator for the season, perhaps four times a year to the voltage appropriate to the average temperature. Cessna used to recommend this procedure in their maintenance manuals.

Now compare the readings taken at the battery (V1) and at the voltage regulator's input terminals (V2). If these two voltages differ by more than 0.1 volts, I would recommend rewiring the regulator per Figure 4-5.

Instruments for electrical systems monitoring in flight are mandatory. Being able to interpret them accurately is just as important. A zero center, battery ammeter (discharge-zero-charge) is the most desirable and should be the first electrical system instrument you install. Interpretation of this instrument is described in the chapter on batteries. An accurate voltmeter would be my choice for the second instrument, but it must be ACCURATE! To be useful, you must be able to read a voltmeter to the nearest 0.1 volts. More on this subject in a later chapter on instruments. The construction articles will include details on building an expanded scale voltmeter that reads from 10-16 volts instead of 0-16 volts.

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