Over Voltage Protection Systems

Before we can launch off on this subject, we need to arrive at a common language to describe system bus voltage aberrations and their causes. One of the historical causes is invoked all too often when the speaker is unwilling or unable to research the real reason for the difficulty . . . .

THE 'GLITCH' DE-MYTHED

Many times in my experiences with electronics, I have heard some presumably informed technician say to some less informed individual (usually the hapless victim), "I guess a glitch got it". He would then proceed to replace the damaged article with a new one. The victim could do nothing more than wonder who or what the 'glitch' was and try to calm his writhing checkbook! The 'glitch' may be personified as a creature of variable size and form which lurks about all manner of electrical device. I have heard it referred to by other names, "gremlin" is quite often used.

Irrespective of how one names the thing it drips with an ooze of excess electrons and breaks into fits of hysterical electrical emissions whenever it finds an a loose wire or exposed bus bar. A glitch will hit targets of opportunity which are more prolific when a mechanic has removed a cover or disconnected a wire for diagnosis of a problem. Therefore, glitches can be expected to hang around an FBO's shop at an airport. They love service stations too; there's nothing more insidious than a glitch that's high on gasoline fumes! Glitches hang around engineering labs too. I've witnessed many events wherein all of the smoke has just escaped from some integrated circuits and the tech says, "#@%&*#$ glitch!". Onlookers nod in solemn acknowledgment. Someone may even open a window; glitches love smoke and hate fresh air.

You've all probably seen the margarine ad on television where the lady declares, "Its not nice to fool Mother Nature!". Well, she's right. It's only fair since Mother Nature will never fool with you. The laws of physics are pretty well understood in the technology we are about to discuss. There is no need to explain anything in supernatural terminology when it comes to working with aircraft electrical and avionics systems. All things have an explanation based on the physics of the matter.

MEET THE REAL CULPRITS

Departures from normal voltage come in four classes which I will call *spikes*, *surges*, *noise* and *faults*. A *spike* is a short duration, low energy departure from normal bus voltage. By short I mean measured in tens of microseconds and the energy is so low than you would never perceive a change of intensity of a small light bulb if a *spike* were applied to it while it was illuminated. A *surge* is on the order of 1000 times longer in duration and measured in tens of milliseconds. The effect of *surge* upon the intensity of an illuminated lamp is visually discernible. *Surges* may even be of sufficient amplitude or duration to cause a failure of various components in the system. *Spikes* and *surges* are usually singular events associated with the operation of piece of equipment in the system. *Noise* is a repetitive occurrence of *spikes*, very small *surges* or a combination of the two. *Noise* may or may not be discernible by observing an illuminated lamp. It most often manifests itself in the effect it has on the operation of another device. Strange sounds in the audio system, erratic operation of an ILS indicator, and Loran-C falling out of lock are but a few ways *noise* may exert an influence. A *fault* is the least obscure of the four. It is the broken connection, the shorted transistor, the failed device which makes itself noticed in very profound ways.

Let me assure you of one fact: there is no electrical system that is totally free of the first three items in this list, unless perhaps your power supply consists only of a battery and its only load is a small radio or perhaps a light bulb. Even the space shuttle has a certain amount of *spike*s, *surges* and *noise* in its electrical system. It comes down to a matter of degree: the ability of designers to limit the disturbances at their sources balanced against the ability to design devices tolerant of some level of disturbance. I am going to deal with the first three of this family later in the chapter on dealing with system anomalies and *noise*. The reason for including so much information here is to make a clear distinction between what an overvoltage relay is expected to protect you from and to describe those things which might disturb an overvoltage relay's ability to function.

THE OVERVOLTAGE CONDITION

Can you recall ever having seen an automobile coming down the road toward you at night with headlights which seemed a little too bright? Remember the sort of blue-white color they had instead of the warm color put off by other cars? That particular vehicle was probably suffering from a failed voltage regulator. The system voltage was past 15 volts and rising. The battery working valiantly to absorb the excess energy and losing. Not long after you saw it the owner of that vehicle was getting it serviced. Failure of the voltage regulator in the automobile is a much more benign experience than a similar failure in an airplane. First, the accessories likely to be damaged by overvoltage are relatively cheap compared to a panel full of solid-state avionics. Second, the loss of components in an automobile seldom presents a life threatening situation.

OVERVOLTAGE RELAYS

The overvoltage relay has roots in the late 50's when a sophisticated avionics package required many amps of generator capability. Radios were vacuum tube devices and high power transmitters had dynamotors for generating high voltages. [A dynamotor is a 14 or 28-volt d.c. motor which shares a common field with a generator rated at 200 volts or more. Not terribly efficient but very simple, rugged and reliable.] During this time aviation electrical system designers were experiencing their first difficulties with large generators of electrical power combined with relatively small batteries. A failure of the voltage regulator could rapidly boost the system voltage to damaging magnitudes.

One of the early production fixes for this problem consisted of a carefully designed combination of relays, not unlike those found in the voltage regulators of the time (see Section 4). An example of this kind of O.V. relay is shown in Figure 6-1. The sensing relay was very carefully designed to pull in at some voltage just above normal system operating voltage. Once it was actuated an extra set of contacts called, "holding contacts", would hold the relay in an energized position until power was removed completely.

These early attempts to address the O.V. protection task were crude and troublesome by modern standards. It was not uncommon for an O.V. relay to be bypassed in the field by frustrated mechanics and owners who experienced ten times more difficulty with the O.V. relay than they did with failed voltage regulators! But they did work most of the time when needed and saved many an aircraft radio from an untimely death.

A simplified schematic of a more modern O.V. relay is shown in Figure 6-2. An integrated circuit known as a comparator is used to sample a scaled down component of the bus voltage at the arm of a calibrating potentiometer. This sample is compared with a voltage reference device, in this case a temperature stable zener diode. Note the arm of the calibrating potentiometer connected to the (+) input of the comparator. The significance is: as long as the arm of the pot has a voltage on it that is below the voltage of the reference diode, the output of the comparator will be low. In an overvoltage situation, the voltage at the arm of the pot will rise above the reference zener's voltage and the output of the comparator will suddenly rise. The SCR (silicon controlled rectifier) will be triggered and the relay will energize, removing bus voltage from the input to the regulator. The SCR shown in this example is really intended for use in a.c. power circuits. It has a close cousin, the TRIAC, which is used in dimmers for ceiling fixtures. When used in a d.c. circuit, the SCR will latch into an ON state the first time it is triggered and remain solidly ON until power is removed from it completely. The latch-up phenomenon insures that once the offending voltage regulator and alternator are shut down, they are not allowed to come back on line when the voltage returns to safe levels as a result of having shut down the failed system.

Earlier I wrote about designing to be tolerant of certain abnormal conditions which may be present on the bus. In the case of the overvoltage relay, one would not wish to be plagued with nuisance tripping of the O.V. protection system due to intermittent and harmless *spikes*, *surges* and *noise*. This is accomplished in part by adding the capacitor C2 from the arm of the calibration pot to ground. The effect of this addition is to slow down the response of the O.V. relay so that the *spikes* and low amplitude *surges* from the alternator system don't cause nuisance trips.

To put the word "harmless" into perspective, there is are a number of specifications published by the *Radio Technical Commission for Aeronautics* otherwise known as the RTCA. One of their specifications is called DO-160 and it deals with the certification of avionics components for aircraft. The document specifies that if a 14-volt device is air-worthy it must be able

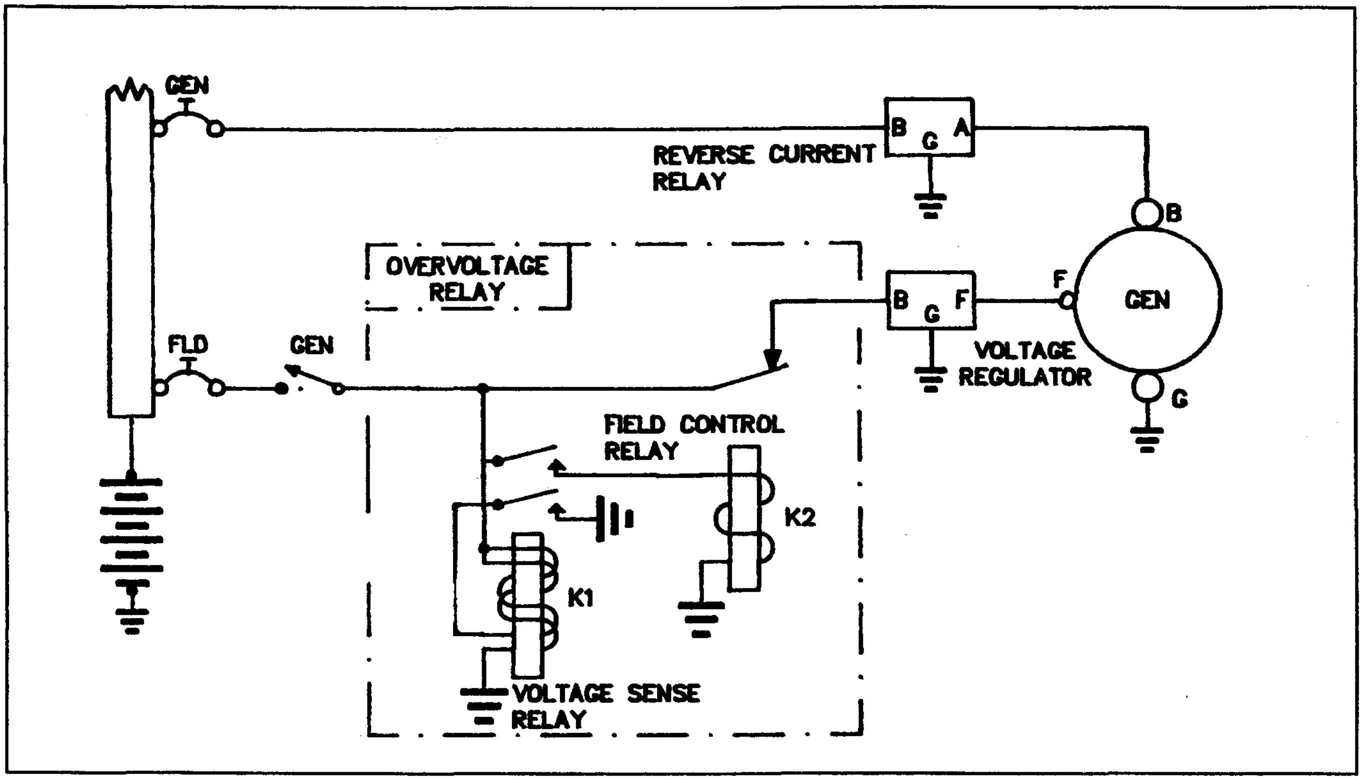

Figure 6-1. Electromechanical O.V. Relay

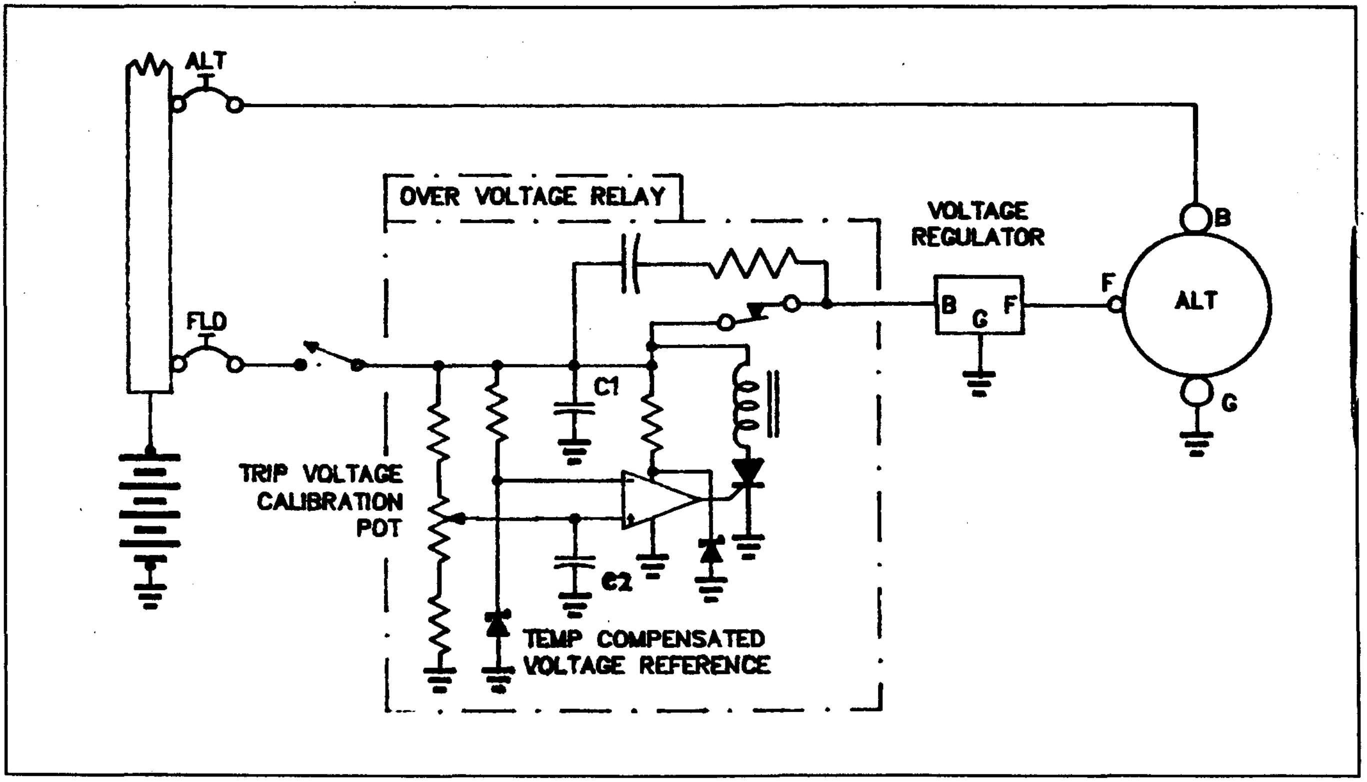

Figure 6-2. O.V. Relay with Electronic Sensing.

to withstand a *spike* of 300 volts in amplitude and 100 microseconds in duration when delivered from a source with a 50-ohm impedance. Without going into elaborate detail, passing this test is a breeze. The *spike* contains very little energy and it is easily negated by the capacitor C1 in the sample circuit shown.

Another paragraph in the spec says a device must be able to withstand *surges* of 40 volts for 100 milliseconds and 20 volts for 1 second periods of time. The spec allows the device to operate in an abnormal manner during the transient, however, the device being tested cannot be damaged by it and must return to normal operation afterward. To comply with this requirement, I simply select components which are rated to operated at 40 volts or more if they are to be connected directly to the airframe electrical system. Example: a 16-volt rating might be sufficient for C1 in normal operating conditions but a 40-volt *surge* would be likely to kill it.

The values 20 and 40 volts, and the times associated with them were selected by the RTCA as being worst case situations. For example, when a voltage regulator fails, a large alternator will begin pushing up the bus voltage in spite of best efforts of the battery to absorb the excess energy. Experience and analysis have shown that the voltage is not likely to rise above 20 volts in less than one second, even with a tired battery, thus giving the O.V. relay time to react and shut down the *faulted* system. Further, if the *fault* occurred with very little or no load on the alternator and with the battery off line, the voltage could be expected to rise more quickly and to a higher value, say 40 volts in 100 milliseconds or less. In the case of O.V. relays, one of the requirements for certification is to be able to sense and contain such a *fault* in 100 milliseconds or less and before the bus rises to more than 40 volts. Here we see the interplay between design to withstand and design to limit. All components certified for flight must be able to withstand this test and the power generation system be designed to insure that these test limits are never exceeded in practice.

For 28-volt airplanes, the test voltages are doubled: a 600-volt *spike* for 100 microseconds, an 80-volt *surge* for 100 milliseconds and a 40-volt *surge* for one second. It is a simple test to make for the products I have certified in the past. First, I make sure an appropriately rated *spike* suppression capacitor is also rated to withstand the *surge*. Then I turn the power supply up to 80 volts for a good count of "two". If my box still works, I'm ready to sell it to the customer.

There is another factor in O.V. relay design that is often addressed badly by some manufacturers. The field of an alternator is an inductive device and capable of storing considerable electrical energy. In order to explain how this happens I will tap your knowledge of another inductive energy storage system, the automotive ignition designed by C. F. Kettering. Bet you never heard of him. Fascinating fellow. His many accomplishments include electrification of the cash register, and designing practical starters and ignition systems for cars. He was also the first individual in the U.S. to have a house cooled by a refrigeration system of his design (Bet you thought Carrier was first!). When its too cold and wet to fly next winter, look Kettering up in the library. His accomplishments have more influence on your daily life than do those of Thomas Edison, however very few people have heard of him.

Figure 6-3 shows the basic components of the Kettering automobile ignition system. Battery voltage is supplied to the primary winding of the ignition "coil" via the closed contacts of what are commonly referred to as the "points". The current flowing in the primary wires sets up a strong magnetic field within the core of the winding. When the points open a curious thing happens. The current in the winding goes to zero and the magnetic field in the core rapidly collapses. The rapid rate of change of the magnetic field induces an electron flow in the many turns of the secondary winding of the coil. This impresses a voltage in the secondary winding on the order of tens of thousands of volts; enough voltage to cause a spark and accomplish ignition of the fuel mixture at the plug.

Figure 6-3 also includes the "condenser" which is an archaic term for a capacitor. Recall that without the condenser, the car runs poorly and the points get burned. The reason for the capacitor has to do with the speed with which the points spread apart upon opening. Remember, the points are opened by a cam which rotates at 1/2 engine RPM and there is a finite limit to cam lift as well as shaft RPM. Air is a pretty good insulator, it will stand off as much as 1000 volts per 1/1000 inch gap. As the camshaft is coming around and the points first open, how big is the air gap between them? The difference between "zero" and "first gap" can be quite small; a very few volts will bridge a gap of micro-inches. As the points begin to open, if there is no capacitor, the current through the secondary of the coil goes immediately to zero. The collapse of the magnetic field has the ability to induce many thousands of volts in the secondary but it can induce several hundreds of volts in the primary as well. This voltage can

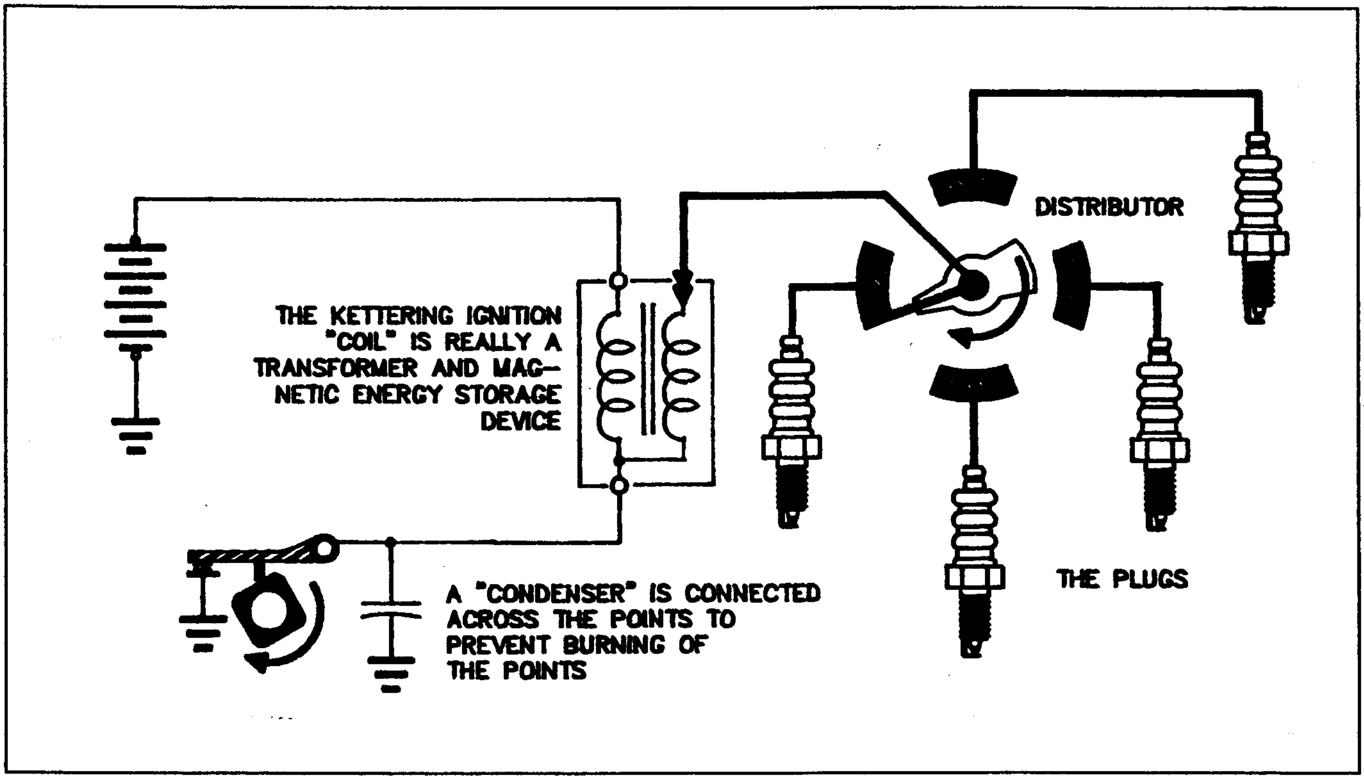

Figure 6-3. Simplified Schematic of Kettering Ignition System.

cause an arc to form across the partially opened points. Once the arc is established between the points, it would continue to grow in length as the points opened further. Energy that would normally be available to cause a spark at the tip of the spark plug is now being lost in heating up the points! Hence poor spark and burned points.

By placing a capacitor across the points, the voltage rate-of-rise (dv/dt for those of you who remember first semester calculus) may be slightly retarded by not allowing the current in the coil to drop immediately. If the capacitor is made too large, the rate of field collapse in the coil will be retarded too much and spark performance will suffer. If the capacitor is too small, it will not prevent an arc from being established between the points as they first open. The electrical size of the capacitor must be adjusted for the best compromise between arc suppression and spark performance. We'll discuss this example in more detail in the chapter on switches and relays.

Going back to the overvoltage relay in Figure 6-2, note the series connected resistor and capacitor connected across the contacts of the relay. The capacitor accomplishes the same job for the relay contacts as the "condenser" did for the points in my '41 Pontiac. When the O.V. relay is tripped, and just as the contacts are opening to break the field circuit, the current in the alternator field must be prevented from collapsing so rapidly that an arc is established and maintained across the open contacts of the relay. If the relay selected was marginal in contact spreading velocity (fancy term for how fast they open), the size of the capacitor and resistor could be critical to the survival of the relay contacts. O.V. relays which actually contain relays should not be used with very large alternators (50 amps or more) unless one knows specifically that the relay and associated arc suppression network are adequate to the task. I have reduced many a relay contact to molten, dead-shorts in the process of determining the proper components for an arc suppression network. For smaller alternators and, if you always have a battery which hasn't been overworked, just about any O.V. relay from a certified airframe can be used by the homebuilder.

Now, let us suppose our voltage regulator has just shorted and full bus voltage on the order of 14 volts has been applied to the field. Inductors resist changes in

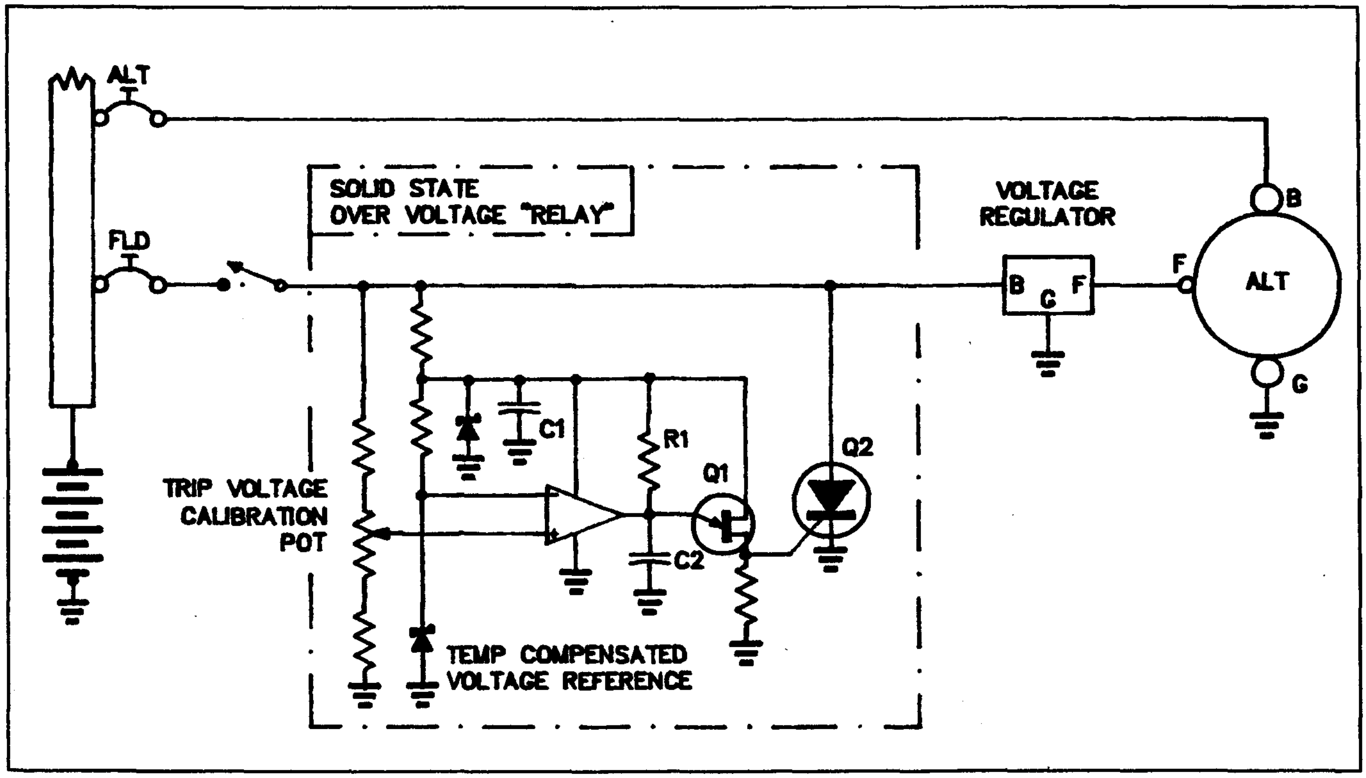

Figure 6-4. The Ultimate Protection, the "Relayless" O.V. Relay.

the current which flow through them. This is true of any inductor whether it is the primary of a spark coil or the field winding of an alternator. The increasing magnetic field in the core of the alternator field causes a counter-electromotive force (or opposing voltage) to be induced in the winding. This is why the "dwell" time on a set of points in the ignition was so important. The points must be closed for a minimum amount of time per spark cycle to allow the coil's magnetic field to build to some minimum level required for adequate spark. This same delay in the build of magnetic field in the alternator prevents an instantaneous rise in alternator output. It rises very quickly but the slope is measured in numbers on the order of 0.2 to 1 volt per millisecond.

The field is connected directly to the output of the alternator via the failed regulator so the process is regenerative. "Regenerative" means the system feeds itself to the physical limits and possibly failure of some component. As the bus voltage climbs, the field voltage climbs causing the bus voltage to climb some more, etc. Were it not for the battery's ability to absorb large amounts of energy for a short period of time, an unchecked alternator failure could push a 14 volt bus up to 100 volts or more in a few hundred milliseconds.

The task of the O.V. relay is to sense an impending system disaster and bring the alternator under control before something smokes. The trick is to be able to discern the 'normal' *spikes*, *surges*, and *noise* from the *fault*. Then, once a *fault* has been identified, the system needs to be shut down in an orderly fashion with nothing more spectacular than a little flicker of the panel lights. Tens of thousands of O.V. relays have been marketed (a goodly portion of them my designs) which are similar in operational philosophy to the example in Figure 6-2. These were certified designs which currently fly on many a heavy, aluminum bird. Over the 15 or so years that I've been involved in these programs I have evolved three criteria for designing O.V. relays: First, consider any voltage over 16 (32 in a 28 volt airplane) as an indication of impending *fault*. Second, if the voltage stays above this level for more than 5 milliseconds, consider it to be a *fault* which proceeds a voltage runaway. Third, shut down the alternator in the most expeditious manner and, if possible, without breaking an inductive load.

It sounds like a tall order but it is quite simple. For those of you who are interested in the electronic details, Figure 6-4 shows the implementation of this philosophy as it was designed for Voyager. Note the arm of the calibration pot does not have a capacitor to ground like the design shown in Figure 6-2. This allows the comparator to "see" an accurate representation of the bus voltage with no smoothing of the *spikes, surges and noise*. The output stage of the comparator is an open collector transistor which is maintained in a turned on condition as long as the bus voltage is below 16 (or 32) volts. When the voltage does exceed the calibration value, the comparator's output transistor turns off and the collector pull-up resistor (R1) is allowed to charge C2 until it reaches the trigger voltage of the unijunction transistor, Q1. The time interval required for R1 to charge C2 to the trigger voltage is independent of the magnitude of the system bus voltage. The size of the resistor and capacitor are chosen to achieve the aforementioned 5 millisecond 'wait and see' interval.

If the bus voltage drops below 16 volts, at any time before the 5 mS timer times out, C2 is discharged thus resetting the timer to zero. If the timer does make it to timeout, the unijunction fires and the charge on C2 is dumped to the gate of the SCR (silicon controlled rectifier), Q2. Once this guy is triggered, a dead short is placed from the field circuit breaker lead directly to ground. The voltage across the field of the alternator is forced immediately to zero by way of the failed regulator and the impending disaster never grows to fruition. All that remains to happen is the opening of the field circuit breaker in response to what it perceives as a wire shorted to ground.

This type of shutdown technique is commonly referred to as a "crowbar overvoltage protection circuit". The "crowbar" technique complies with Nuckolls' third law of O.V. protection. In placing the short from the field supply to ground, the energy stored in the inductive component of the alternator field is harmlessly dissipated in the resistance of the field wire instead of in the air gap of some poor relay contact. The inductive circuit is never 'broken' but rather tied to ground though the fired SCR. The field circuit breaker does 'break' a current flow. However, it is not an inductive field circuit but rather a simple short to ground; just exactly the kind of situation the breaker was designed to take care of!

I have a story to tell about crowbar overvoltage protection systems. While in the employ of a Wichita based aircraft components manufacturer, I had been trying for a number of years to get the heavy aluminum bird people to consider the crowbar O.V. protection technique. The usual response to my suggestion was, "What we have now works. It's certified. No customers are complaining. Why change?" It's a damn powerful argument in the certified airplane business and it tends to bury the future in antiquity! One day about eight years ago I received a call from a man in a test lab who was trying one of our production linear regulators with a built in O.V. relay in the mockup of a new system being developed for a single engine turbo-prop. On turbines, the alternator spins at 9,000 to 11,000 RPM in cruise. It seems no production O.V. relay available to this individual could handle this fire-breathing, 70-amp beast in an over-voltage condition. They had a certification requirement that the O.V. relay must catch 50 simulated failures in a row with a bus voltage excursion no higher than 40 volts! All products tried, including ours, had failed after a few O.V. trips. Furthermore, on the few times when successful shut downs were achieved, the bus voltage excursions were something to behold; the panel light bulbs in the mock-up were being replaced regularly in the course of his explorations.

Did I have a deal for him! I modified one of our production units to include a crowbar O.V. system not unlike the one shown in Figure 6-4. I was out to his lab in less than two hours. He connected my prototype into his test setup and prepared to run the first test at reduced RPM, battery on line, and with some electrical loads turned on. I told him, "Nope, crank it up all the way, turn off the battery and kill the loads." He was skeptical but he did as I asked. When he punched the *fault* button, nothing happened! The mockup panel lights barely flickered and he thought his *fault* simulator had failed. I pointed to the now popped field circuit breaker and to the chart recorder which indicated a rise to 32 volts had occurred, just before the system was shut down. I told him to try it 49 more times if he wished, even a hundred, and let me know how it worked out. I needed to get back to my office. I knew the first thing to fail was going to be his field circuit breaker and it was rated for thousands of operations!

He called me later in the day. He said we were a shoo-in for the alternator control system on the new airplane; he'd never seen anything like it. I told him I'd been trying to sell the system into the airplanes across the field from him for years but the status quo was king. He allowed as how their latest-and-greatest would carry our system and perhaps it would trickle down into the rest of the product line later.

A few weeks later, they canceled the program; no market for the latest-and-greatest. When we had the opportunity to do the alternator control unit for Voyager, one design decision for the system was already made, tried and proven! To this date, I know of no production lightplane flying such an O.V. protection system. However, B & C Specialty Products has produced a couple of hundred LR-1's and LR-2's. You guys know a good thing when you see one! In the construction articles we plan to do a design and provide a source for the etched circuit board for the construction of a crow-bar over voltage protection system suitable for homebuilt aircraft.

FAIR GLITCH, WHERE HAST THOU GONE?

The emphasis of certain words in this section was done as an aid to understanding; to plant the seeds of some concepts which will be addressed in more detail in later sections. Notice our whimsical friend "Glitch" received little than a dishonorable mention. By the time we've published on the full range of topics in aircraft electrical and avionics systems, you should have a better handle on bus voltage anomalies than most of the licensed mechanics and technicians I have known . . . .