



## 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.

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**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].*

*By the time I got Clarksburg set in the handheld GPS we were in the clouds, and I was wandering 30 degrees on either side of my assigned heading. Suddenly, I remembered my passenger, gave him another flashlight, and asked him to shine it on the panel. This freed up one of my hands and allowed me to use my smaller flashlight to read the approach chart. Occasionally during the descent, I turned the battery back on to get a new heading from the controller. On one occasion, the controller told me that a departing aircraft had reported the ceiling at about 1,000 feet AGL. He suggested a visual approach. I'd been planning on an ILS, but I wasn't flying too precisely, so a visual approach had some appeal.*

*Once I reached 2,500 feet, I again turned on the battery and called the controller. He asked repeatedly if I had ground contact beneath me, and I repeatedly told him that I did not. Four miles from the field, I conducted a prelanding checklist and was able to lower the gear with battery power.*

*When I broke out of the clouds I saw bright lights at 11 o'clock, where the controller and the GPS said the airport should be. I wasn't sure that it was the airport I was looking at, seeing no runway lights, rotating beacon, or approach lights. I descended slowly to 500 feet AGL without positively identifying the field. Eventually, the GPS confirmed that the airport was behind me, as did the controller. Once I surrendered the navigation task to the controller, I had allowed myself to lose situational awareness - despite having two GPS receivers. I turned to the right and saw the runway lights.*

*On short final, I thanked the controller for his help and made a normal landing.*

*There are some important lessons that I took away from this flight.*

*Land first, fix it later [4]. At the first sign of an electrical malfunction, I should have landed. Waiting for the smoke and sparks to make the decision for me was stupid. I had a stable situation until I started troubleshooting it. As I learned later, the voltage regulator had failed, sending too much charge to the battery-which was indicated by the pegged ammeter [5]. Coincidentally, the alternator circuit breaker did not trip to protect the rest of the electrical system [6].*

*Fly the airplane. While fiddling with the avionics, I allowed my heading and altitude to wander.*

*Navigate. Once I had allowed the controller to vector me, I essentially stopped navigating. Had I lost commu-*

*nications at that point, I would have spent several precious seconds flying around at night, in clouds, over mountains, while determining my position.*

*It pays to be prepared. I would have been more scared had I not carried two flashlights, extra batteries, and a handheld GPS receiver. It pays to play "what if" scenarios through your mind during those hours of boredom.*

*Get help wherever you can. The Clarksburg Approach controller made a great copilot. He took over navigation and terrain clearance, though probably more than I should have allowed him to. Your passengers can help, too; they can pump the gear, hold a flashlight, fold a chart, and more.*

*Martin Gomez, AOPA 830204, an engineer from Fairfax, Virginia, is a 675-hour commercial pilot.*

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I congratulate pilot and author Gomez for his resourcefulness and skill in bringing this event to a happy ending. Further, I appreciate his willingness to publish his experience for our benefit. Critical review like that which follows is not intended to demean the author or diminish his stature in the community of aviators. One purpose of this chapter is to demonstrate how Mr. Gomez and our fellow aviators have been trapped by circumstances which need not have happened. I will suggest design and operational philosophies that will allow us to fly for the next fifty years "never again" having to experience this kind of problem. Let's look at some data points in the article:

[1] *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.*

This is a clear indication of either regulator failure or a shorted cell in the ship's battery. If the airplane had a voltmeter, momentarily setting the alternator field switch at OFF would confirm the diagnosis. If bus voltage falls to 12.0 volts or above, the battery is okay and the regulator is failed. If the bus voltage falls to a bit above 10 volts, then the battery is shorted. Battery shorts are very rare compared to all other battery failures so it's most likely that the regulator has failed. What happened to the ship's overvoltage protection system?

[2] *After all, I might not be able to land at Clarksburg, and I wanted to keep the battery charged to power the ILS receiver. He vectored me toward Clarksburg.*

Our hero's first concern after taking the alternator off line is keeping needed avionics running. Since he was in a rented airplane it's a sure bet he didn't know what the ship's battery capacity was. This lack of knowledge forced him to shut down essential systems until the final minutes of the flight.

**[3] *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.***

The C-172 has overhead flood lighting that draws just under 200 milliamps. Much preferable to holding a flashlight in the teeth. None-the-less, with the master switch OFF, it was unavailable to him.

**[4] *Land first, fix it later. At the first sign of an electrical malfunction, I should have landed. I Waiting for the smoke and sparks to make the decision for me was stupid. I had a stable situation until I started troubleshooting it.***

Throughout my writings and conversations with builders, I've encouraged pilots to leave their toolbox closed until safely on the ground. Unfortunately, the electrical system architecture and operating limitations built into most certified aircraft make it tempting to do in-flight diagnosis and repairs. It's distracting to an already busy pilot and may make the problem worse.

**[5] *As I learned later, the voltage regulator had failed, sending too much charge to the battery-which was indicated by the pegged ammeter.***

Correct . . . but his mechanic said nothing about (or worse yet) didn't know about ADDITIONAL problems with the airplane. Where did the sparks come from? Something behind the panel was exposed and faulting to ground. What happened to the overvoltage protection? Was this built into the voltage regulator and fixed with a new regulator. OV protection might have been a separate and overlooked component, still in a FAILED condition and waiting to ignore the next regulator failure?

**[6] *Coincidentally, the alternator circuit breaker did not trip to protect the rest of the electrical system.***

A very common misconception about circuit breakers. The alternator's main output breaker almost never trips in an OV condition. Alternators are current limited devices meaning that while the bus VOLTAGE is climbing, output CURRENT from the alternator is only a few percent above the alternator's rated output which should NOT open the breaker.

The alternator's field circuit breaker is expected to open during overvoltage IF the airplane is fitted with a crowbar overvoltage protection device . . . I'm reasonably certain this airplane was not so equipped.

As I suggested earlier, this article is not unlike many, many others we've all read for decades. I think you'll agree that they all end the same way. "Sure glad I did this . . . next time I'll do that . . . boy! I'll never do this again." Have you ever read an article where the author questions either the manufacturers or regulators of airplanes as to what might be done to reduce if not eliminate the probability of a reoccurrence? We're schooled as pilots and mechanics that somebody knows a lot more about airplane design and safety than we do. We're taught further that once these bastions of knowledge and public interest pronounce aviation products fit for sale to the public, the notion of making any changes for the better are overwhelmed by bureaucratic roadblocks and ignorance.

What are we really looking for when using words and phrases like "reliability" and "failure rate"? For the majority of designers, manufacturers and users in the aerospace industry, these words bring up mental images of individual components carefully designed, tested, procured, installed, maintained and used in accordance with thousands of words of documentation.

Many of the documents are specifications, regulations or rules which (if not dutifully complied with) can be the basis for punishment of individual(s) who do not faithfully follow the words irrespective of motivation. How about Mr. Gomez's C-172RG? How much of the script for his harrowing experience was written by industry and government authors?

Mr. Gomez's story has ratcheted up the worries of perhaps thousands of pilots. References [5] and [6] highlight omissions and misconceptions in the story. These can also contribute to uncertainty on the part of folks who don't do this for a living yet are obligated accept the airplane as-is-where-is. Manufacturers might have an interest in upgrading their products but regulators often make this an expensive and time consuming task. Further, when a product is so highly regulated, manufacturers tend to relax . . . after submitting their product to the will of government, it must surely represent perfection! This is the biggest reason why aviation lags decades behind virtually every other industry.

That leaves it up to our hero to do whatever he can within his limited understanding of the system to plan his own actions for the time when he may expect to encounter this problem again.

Aviation journals appreciate these stories too . . . they get a reader's attention and in some small way, publishing them may indeed improve some pilot's chances of dealing with a similar situation. This lends some validity to the publisher's stated mission of improving on aviation safety.

The very same issue of AOPA Pilot carried an advertisement from a company that takes money from pilots to prepare them for these events. A testimonial from a former student congratulated himself for having taken the training course. The pilot said something like, "Only weeks after having completed this course, my efforts were rewarded when I successfully handled total electrical system failure in my airplane." The author of these words is justifiably proud of the success he experienced by training for a very stressful airborne situation. Ignorance is a strong pacifier and fear is a still stronger motivator. A combination of fear and ignorance is useful when it comes to extracting money from people with the feel-good mission of making a pilot more confident and capable of dealing with airborne adversity. The sad facts are that contemporary electrical systems are so untrustworthy that such training courses are valuable.

Aviation in the US deals with system inadequacy by striving for failure reduction, an increasingly expensive task as the numbers and kinds of failures become more random and rare. When system shortcomings are noted, they're more likely to be treated by add-on hardware, new regulation and/or additional pilot training rather than to fix the root problem.

The most elegant solution yet is totally unheard of in contemporary certificated aviation . . . design systems so that most failures of the nature described by Mr. Gomez don't matter. Failure tolerant design is much easier, lighter and less expensive to build than contemporary certificated designs.

For years, I've been working with amateur airplane builders who have chosen NOT to be ignorant. None-the-less, they bear heavy baggage brought with them for having read pilot's journals and listening to hangar tales of nail-biting escapes. Unlike the folk who swing wrenches on certificated aircraft, the amateur builder is encouraged to think outside the box and free to consider the value of doing something because analysis shows the action to have beneficial effect.

I wonder how Mr. Gomez might have summed up his experience if he knew that for \$15 in parts, a few hours work on the airplane and NO new training or preparation, his story would have been so ho-hum that it wasn't worth publishing?

How would you describe a reliable flight system? May I suggest this:

**"System reliability is optimal when I can suffer any of the most common failures and still put the wheels on the ground, at my intended destination, without breaking a sweat."**

I present forums and weekend seminars around the country on the topic of aircraft electrical systems. One of my favorite questions of an audience is to rank components of the flight system with respect to the need for absolute reliability. I get some interesting comments from the crowd but here's my personal list of reliability priorities:

#### I. Airframe

1. Surfaces
2. Structure
3. Flight Controls

#### II Pilot

1. Skills
2. Training
3. Physical Condition

#### III Power Plant:

1. Engine
2. Propeller
3. Fuel System
4. Controls

#### IV. Systems

1. Electrical
  - (a) Panel Lighting
  - (b) Primary Nav Radio
  - (c) Transponder
  - (d) Turn Coordinator
  - (e) Fuel Pump/Transfer
  - (f) Engine Support

#### 2. Landing Gear

etc.  
etc.

The airframe and other things that make the airplane flyable are at the top of the list. Most people are surprised when I put the pilot as number II on the list. Consider that if the airplane is hanging together, the pilot is skilled and in good physical condition, the chances of living through the

circumstances of any given flight are greatly improved. Of course, if everything lower on the list is kaput, the pilot has few options. However, assuming the engine is delivering enough power to hold altitude, only then do the options begin to include choices for WHERE you will land and HOW you're going to get there. Note that I've ranked electrical system goodies a distant fourth place.

Let us consider life's little benefits that provide the maximum reduction of sweat. I put lighting first on the list. Recall that our hero's most immediate problem upon loss of the electrical system was being able to see. I mentioned earlier that the overhead flood light in the airplane has a very small electrical energy budget . . . but given the way most certificated airplanes are wired, the flood lights are DARK any time the master switch is OFF.

Second on my list is the primary navigation radio . . . VOR, GPS, Loran . . . etc. One solid state radio receiver draws about 0.2 amperes . . . not much energy needed here either.

Third is a turn coordinator . . . generally the only electric flight instrument on the panel and it will save your buns if you are practiced in its use (remember item II. 1 - Pilot Skills?).

Forth comes the transponder. If you've got a situation placing a graceful return to earth at risk, then a 7700 squawk will go a long way toward getting airspace in front of you cleared of other aircraft with no other taxation of your time and attention than to set a few knobs.

Obviously, that list can and should be modified to accommodate your personal flight habits. If you NEVER fly at night, panel lighting isn't an item high on your list. If you NEVER get close to clouds, then perhaps you don't need to worry about the turn coordinator. Further, if your engine is electrically dependent, then perhaps fuel management, ignition and other controls would move to #1 on your list. If you share my fondest dream where vacuum systems are used only for carpet cleaning, your electrical system's architecture for reliable flight will have to accommodate the additional tasks.

Some omissions from my list brought quite a few questions from the audience . . . how about the Comm radio? Engine instruments? Autopilot? Consider this when deciding what goes on your ME<sup>2</sup>L (Minimum Electrical Equipment List): In order to keep an electrical system condition from becoming an emergency, we need to make a list of those things which are most useful in keeping you airborne with enough electrical assistance to maximize probability of comfortable termination of flight.

If we're dealing with an alternator out situation, then the goal is to run just those goodies that help us fly and navigate while minimizing loads on the battery. When you take off, there is one critical commodity on board that puts an absolute limit on time aloft . . . FUEL. Since that limit already exists, let's try not to impose any new limits on endurance. Let us see if we can design and maintain the system so that critical electrical system endurance is equal to or greater than fuel endurance.

Getting back to the Comm radio . . . how much help is the guy on the ground? Assuming you are skilled enough to use the equipment on your ME<sup>2</sup>L, do you really NEED ground based assistance? Wouldn't it be a good idea to assume that it's not going to be available? Besides, when you're busy doing your job in the cockpit and doing it right, I'll suggest that the guy on the ground can become more of a distraction than a help. Recall some of Mr. Gomez's comments about how much of his own duties he turned over to the guy on the ground and how it caused our hero to overshoot the airport and descend too low . . .

Does this mean that the Comm radio shouldn't be on the essential bus? No, but it does suggest that while you're in a minimum power consumption mode, it may serve your mission best to have the radio OFF. Tell the guy on the ground what's happening, what you're going to do and let him know that you'll be back in touch at some waypoint close to your intended destination and only after your safe arrival is assured.

Which brings up another point . . . the essential bus need not be LIMITED to the critical items on your ME<sup>2</sup>L . . . however except for devices that you want to have running under every condition, any E-bus powered device should have its own ON-OFF switch . . . most avionics do.

Autopilot? If you have one, especially a low current wing leveler, you might have it on the essential bus . . . but while you're boring holes in the sky between waypoints, you might improve your electrical power condition by hand flying the airplane except when you have to deal with maps and/or nav radios. Engine instruments? When was the last time you heard of an engine stopping because you didn't know what the oil pressure was? If you're in cruising flight and every engine instrument goes down, how does that impact the probably outcome of your flight? Engine instruments don't help keep an airplane airborne.

Many airplanes are being constructed with electronic ignition and/or electronic controlled fuel injection. These must become a part of your ME<sup>2</sup>L and essential bus planning. Planning is pretty easy and you do it like this:

Add up the current draw of all the goodies that you need to stay airborne and do a good job of navigation to a point where the airport is in sight. In the case of Mr. Gomez's airplane, the load might have looked like this:

Panel Flood . . . . . 0.08 A  
 Nav Radio . . . . . 0.20 A  
 Turn Coord . . . . . 0.30 A  
 Transponder . . . . . 1.50 A

Hmmm . . . the transponder is the only thing that doesn't help him do his job but it draws the most power!!! Anyhow, this list of things adds up to 2.1 amperes. Let's suppose that instead of flying in through an airport rich area of the country, he was en route from Dalhart, TX to Santa Fe, NM and had several hours of simple straight and level flight over lots of dirt, rocks and coyotes. Wouldn't it be a good idea to plan an arrival at his intended destination where there is probably assistance, tools and parts to repair an airplane? Why force a deviation into unfamiliar territory just to accommodate an under-designed electrical system?

The optimum design says that if we've just punched through a cloud layer to VFR over the top and have an alternator crap out (or sparks and smoke from behind the panel) it should be possible to fly to intended destination and make a comfortable arrival with only the battery energy on board. If you had the list of goodies running that I've show above, would you have any problem getting where you were going? In fact, you might even shut the transponder OFF on that leg from Dalhart to Santa Fe. There's not much out there!

Okay, let's leave the transponder on and crank the numbers. 2.1 amperes for 3 hours is 6.3 ampere hours. Aha! We've got a 24 a.h. battery on board, no sweat! Really? First, consider that it takes about 1.0 amps just to keep a battery contactor closed. Second, what is that battery's capacity after three years on the firewall, two episodes of leaving the master switch on and one case of exposed plates due to poor water maintenance? Just because a battery got your engine started doesn't mean that it has the capacity needed to supply your minimal electrical system needs.

I'd go so far as to suggest that half the airplanes flying today carry a FAILED battery. If the airplane suffers alternator problems *the battery doesn't have enough energy to carry ME<sup>2</sup>L for the duration of fuel on board.*

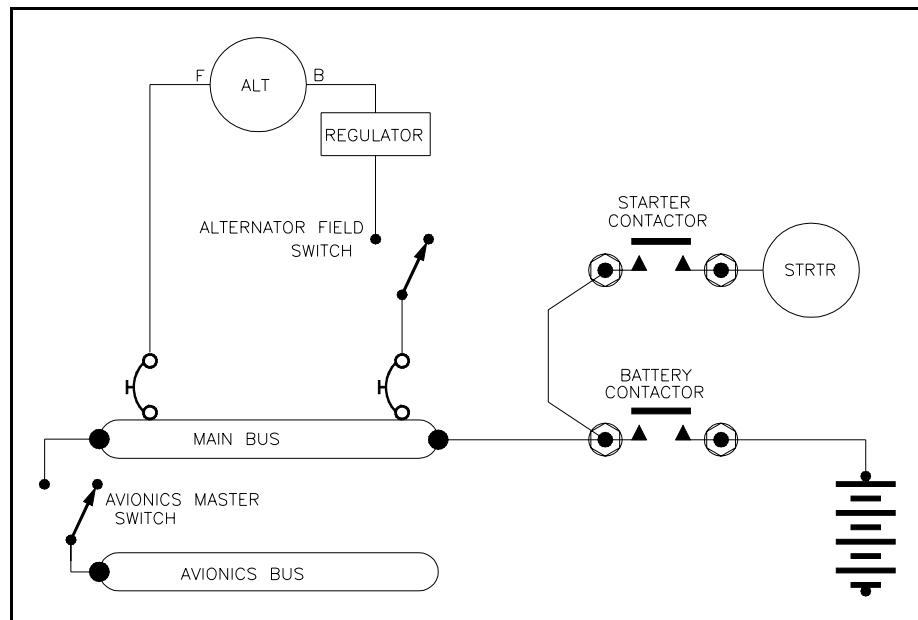


Figure 17-1. Rudimentary Single Battery, Single Alternator Power Distribution System.

Two important factors contribute to this condition. (1) There is no industry standard practice that routinely checks an aircraft battery for current capacity. Batteries get replaced when they fail to crank the engine for the second, third or perhaps even tenth time. (2) There is no industry standard practice for electrical system architecture that allows a pilot to flip a couple of switches and fly on - confident in the knowledge that necessary electrical system goodies will function all the way to intended destination.

As builders of the finest airplanes to ever fly, you have the option of rectifying these two conditions such that stories like that told by pilot Gomez will never be a part of your personal life experience. Before improvements can be proposed upon contemporary certified aircraft electrical systems, we should consider the state-of-the-art flying in the vast majority of single engine airplanes.

Figure 17-1 illustrates the factory wired configuration for pilot Gomez's Cessna 172RG. Noteworthy points to ponder include the traditional practice of routing the alternator's power output lead (often called the B-lead) directly to the main bus inside the cockpit. There was probably an avionics bus with a single power feed through an "Avionics Master" switch. This particular theme for power distribution has been standard on single engine aircraft since the mid 60's. Had pilot Gomez's airplane been wired a bit differently, the course of his experience could have been much different.

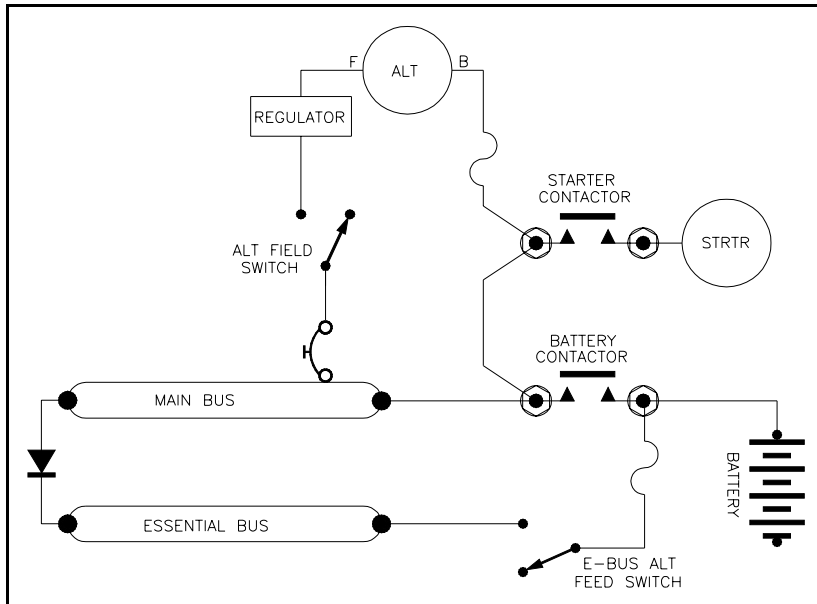


Figure 17-2. Single Battery, Single Alternator System with Dual Feed Essential Bus.

Figure 17-2 makes three important modifications over the system described above. First, the alternator B-lead is tied into the power distribution system on the firewall using an in-line fuse instead of a circuit breaker. This change provides for a much lower resistance path between the alternator (the noisiest device in the electrical system) and the battery (the best filter in the electrical system). An important feature of this change is to size the alternator's B-lead fuse such that nuisance blowing is not going to happen. Most certified airplanes with 60A alternators also have 60A breakers in their B-lead feeds. Under certain but not uncommon conditions, a 60A alternator's output can exceed its rated value and trip the breaker. Tens of thousands of certified aircraft have an alternator breaker *designed to nuisance-trip*. The B-lead breaker recommended for a 60A alternator is not less than 70A. A B-lead fuse should be 80A.

Another feature is the reconfiguration of what used to be an avionics bus into an essential bus with important new duties. Recall the list of essential goodies we developed earlier? Things like minimal panel lighting, turn coordinator, and perhaps the system's voltmeter would be fed from the essential bus.

Note that the avionics master switch has gone away. It hasn't been needed for over

20 years. Worse yet, it has been a single point of failure for every device on the avionics bus. In its place, I show a diode that provides the normal power path for essential bus equipment. Any time the main bus is hot, the essential bus is hot.

The most important feature in Figure 17-2 is the alternate power feed path between the battery and the essential bus. This power pathway supplies essential bus accessories even if the main bus has been shut down. Further, it's independent of the battery contactor. If you're in an alternator-out mode and need to conserve battery energy, then the approximately 1 Amp draw needed to keep the contactor closed is eliminated. A battery contactor draws more power than 2 navigation radios!

With a slight rearrangement of the breaker panel in pilot Gomez's airplane to (1) group our previously developed list of electro-goodies on an essential bus and (2) add a normal feed diode and (3) replace the semi-useless avionics master switch with an essential bus alternate feed switch to an always hot battery feed, his experience might have been so ho-hum that the magazine wouldn't have been interested in publishing it. Of course, it's not enough to simply add some parts and rewire a few of the airplane's appliances. The battery must be maintained in a manner that assures adequate readiness in the face of alternator failure.

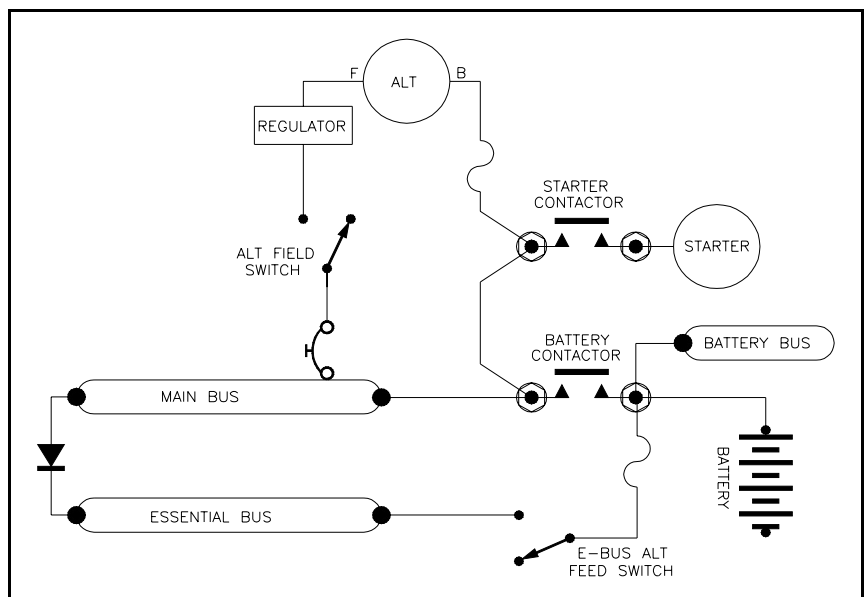


Figure 17-3. . . . Addition of an Always Hot Battery Bus.

Pilots and engineers faithful to the concept of an avionics master switch have suggested that the essential bus normal feed diode be replaced with a switch. You still have dual power paths to the E-bus and all goodies sensitive to the legendary gremlins of aircraft electrical systems can be totally isolated from the bus by opening the switch.

Several things to consider here: (1) most of the gremlins of days gone by either never existed or have been tamed by application of simple engineering solutions (2) except for gross overvoltage conditions, modern radios are by design, regulation, and corporate initiative immune from anything a normally operating aircraft electrical system will throw at it, and a very important (3) if the diode is replaced by a switch, it is incumbent upon a pilot to operate the normal and alternate feedpath switches in the proper order so that the main bus doesn't draw power through the E-bus alternate path and open its fuse or breaker. If you gotta have an avionics master, place it in series with the diode.

Another common objection to the diode is based on the fact that all diodes have a voltage drop of approximately 0.6 volts. I'll suggest this drop is not significant and here's why.

If the alternator is operating normally with a main bus voltage of 13.8 to 14.6 volts, then the essential bus sees no less than 13.2 volts. If the alternator fails and one is dependent upon battery-only operation, the E-bus voltage with the alternate feed switch closed will be 12.5 with a fully charged battery and drop to 10.5 volts at end of life. If you expect all the goodies on your E-bus to provide valuable service when operated from a battery over the range of 10.5 to 12.5 volts, why would you be concerned if the normal operating voltage is 13.2 to 14.2 volts due to diode drop?

Figure 17-3 builds on this new concept by adding an always hot battery bus. This might be a small fuse block of 6 or so fuses. The always hot bus powers things like the electric clocks, dome lights, hour meters, and a single electronic ignition backed up by a magneto. Why electronic ignition on the hot bus? I'll suggest that an electronic ignition need not behave any differently than a magneto with respect to cockpit switches. Any time an ignition switch is ON, that system is hot and ready to run an engine. By operating the electronic ignition from the battery bus, the entire electrical system can be shut down with no adverse effects on engine ignition.

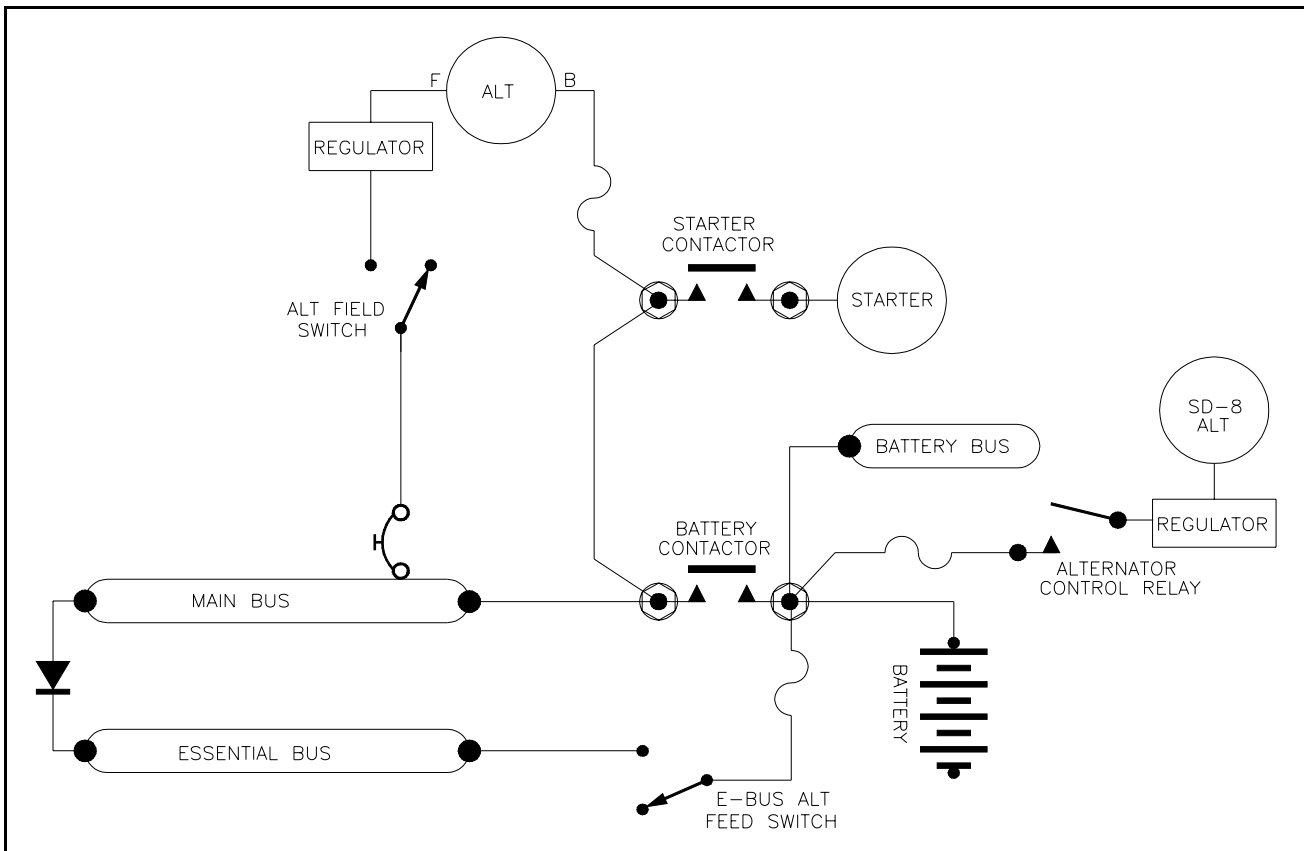


Figure 17-4. Adding the SD-8 Auxiliary Alternator



Would you like to get rid of the vacuum system with its attendant pumps, hoses, fittings, filters and regulators? How about an all electric panel? Yes, I know that electric gyros are more expensive than an attitude indicator but consider this:

B&C Specialty Products offers two sizes of alternators that will operate from a vacuum pump pad on the back of your engine. An 8A model (the SD-8) and a 20A model (the SD-20). Both of these alternators have exemplary pedigrees with failure rates less than one per 100,000 flight hours. Suppose you left the vacuum system out of your airplane and installed the SD-8 alternator in its place.

Figure 17-4 suggests a way to incorporate the SD-8 into a two alternator, single battery electrical system with an excellent reliability analysis. Recall earlier when we were adding up lights, radios and instruments to deduce the E-bus

loads? If you're considering electrically dependent ignition or fuel delivery systems, battery support of electrical loads during alternator-out operations may require an unpractically large battery. In these cases, a second alternator is the solution. The architecture described in Figure 17-4 is the easiest way to make it happen.

Note that with the battery contactor open, the E-bus alternate feed switch closed and the SD-8 alternator control relay closed, you have a rudimentary but complete electrical system that runs all of your essential electro-goodies with unlimited endurance while saving the battery until the airport is in sight.

If the main alternator is functioning, you can leave the battery master closed for normal operations. If the main alternator is down for any reason, you move the DC power master to OFF taking the alternator field off line, close the

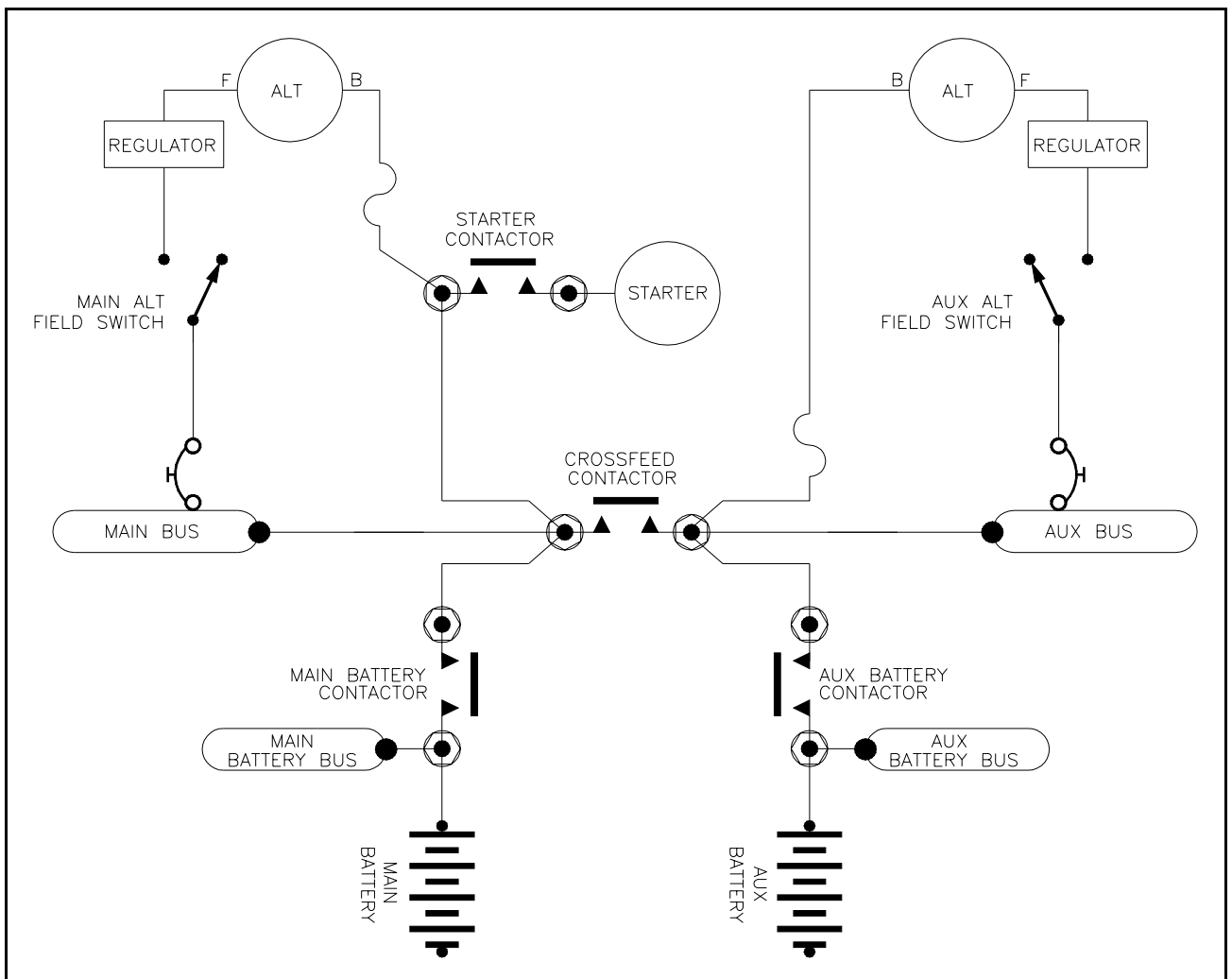


Figure 17-5. Dual Alternator, Dual Battery Electrical systems.

alternate feed path switch for the essential bus and close the aux alternator control relay to configure your electrical system in a manner that is almost identical to that used in hundreds of cross-country, VFR Vari-Ez and Long-Ez aircraft.

Without the auxiliary alternator, the battery must be depended upon for all electrical energy for comfortable continuation of flight. Once you add a second alternator, the battery is relieved of carrying en-route loads and can be saved until the approach phase where you might wish to show some lights or lower landing gear, etc.

It's still a good idea to replace the battery when its capacity drops below a few hours endurance with no alternators. However, once a second alternator is added the battery is relieved of competition with remaining fuel for flight endurance. I proposed this system architecture on a half-dozen or so internet list-servers and the response was immediate and positive.

To mitigate the expense of two electric gyros in the all-electric panel, consider the following option: install the attitude indicator first. Go ahead and punch a hole for the DG but put off buying it until later. With only two wires to hook up, it's no big deal to add it later. Consider that you get excellent heading info from Loran or GPS. Consider also one of the low cost, digital display magnetometer compasses instead of a DG. I could handle an airplane quite nicely with an attitude gyro and accurate heading and course data from electronic sources.

### **Dual Alternator/Dual Battery . . . the mother of all electrical systems. . . .**

Every light twin I know of has a single battery fed by two engine driven power sources. Since generators will run well without a battery, the older airplanes have three, relatively independent sources of power. . . . well, probably only two good sources cause even the guys flying with two fans will flog a battery until it simply fails to crank an engine.

When you trade generators for alternators, loss of a battery contactor may well precipitate total loss of electrical power. Alternators don't run well without a battery. The dual alternator/single battery system common to US built light twins suffers a second problem. To balance loads between two alternators feeding the same bus, it's necessary to maintain voltage adjustments to within a few hundred millivolts of each other. If one regulator drifts upward in setpoint, the alternator it controls will hog all the load. If the setpoint drifts downward, the alternator it controls will shed its loads onto the other alternator. This inability to maintain

an accurate balance in no way diminished the reliability offered by redundant alternators. However, it's was disconcerting to twin engine pilots to observe large differences in alternator output. About 1982, this writer participated in the successful design of a paralleling regulator system for alternators that maintained balance between twin alternators within a few percent of total load.

If you have places on the engine(s) to drive two alternators, then why not exploit the potential for a truly redundant, extraordinarily reliable electrical system? Figure 17-5 illustrates an electrical system that light twin pilots can only wish for. This distribution architecture is equally applicable to single or twin engine airplanes. Most of my experience with this system has been on the larger, more completely equipped aircraft ranging from Glasairs up through the Lancair IVP and even a Venture or two. To date, I'm aware of two or three RV-6 aircraft slated to receive a DA/DB electrical system.

An inspection of Figure 17-5 shows two, independent battery-alternator systems with a "crossfeed" contactor. During normal operations aloft, the crossfeed contactor is open and each system functions independently. If you trace out the details of the DA/DB alternator system described in Appendix Z, you'll find that I've combined the crossfeed and starter control in a single S700-2-50 switch. Pressing the switch to a spring loaded full up position closes the crossfeed contactor and energizes the starter; both batteries assist with engine cranking duties. When the engine starts, the switch is released to spring return to its middle, crossfeed only position and then moved to the full down OFF position.

If one alternator fails, the pilot has the option of moving the crossfeed contactor switch to the middle crossfeed only position allowing the remaining alternator to power electro-goodies on both systems. The two alternators do not need to be the same size. The most common installation in amateur built airplanes uses a 40 or 60 amp main alternator and a 20 amp auxiliary alternator. Unlike most examples of certified alternators for single engine aircraft, modern products have a demonstrated failure rate of less than 1 in 100,000 flight hours. Two such alternators teamed as depicted in Figure 17-5 should live up to your highest expectations. The architecture in Figure 17-5 is being considered for the next major features update on the A-36 Bonanza currently being developed under the auspices of NASA's AGATE program.

If both batteries are recombinant gas technology, then either battery is capable of cranking the engine. The crossfeed contactor makes both batteries available for improved cranking performance.

**Variations on a theme . . .**

There are two important variations on a theme I'd like to discuss now. First, one may consider adding a second battery to the architecture of Figures 17-2, 17-3. One could add a second battery to Figure 17-4 but the value of doing so will be overshadowed by the second engine driven energy source.

Two batteries will co-exist nicely on the same bus contrary to many well intentioned but misguided warnings about the inadvisability of doing so. This is because batteries charge based on VOLTAGE applied to their terminals. It makes no difference whether you have one or a dozen batteries, a bus held to 14.2 volts by an alternator will charge every one of them. A discharged battery cannot be charged by nor present a serious drain on a charged battery. A battery needs something on the order of 13.8 volts or more to become fully charged. A battery delivers energy at 12.5 volts and below. There are no practical concerns for batteries to share a load. Consider what happens when a battery is tasked with engine cranking. If either battery in a two battery system is capable of cranking the engine, then adding a second battery can only have the beneficial effect of offsheding some of the load from the first battery . . . it matters not if they exactly share.

During alternator out conditions we expect a battery to supply ship's loads. The only reason to install two batteries is for the purpose supplying independent power sources to each half of a dual ignition system or dual fuel delivery system on an electrically dependent engine. When the alternator quits, the batteries are split off to separate task assignments . . . again, there are no practical concerns for load sharing.

Last, antiquated concerns for a battery "failure" dragging down the rest of the system are simply not founded in the physics of modern battery construction. RG battery reliability and performance supplemented with good preventative maintenance drives probability of gross battery failure to zero.

Figure 17-6 illustrates the methodology for adding a

second battery to your aircraft. Each battery has its own always-hot battery bus. The main battery bus might have taps for E-bus alternate feed, #1 electronic ignition, #1 fuel injection system, etc. The second battery's bus might carry only the redundant engine loads and accessories that benefit from an always hot feed like the engine hour meter and electric clock.

This architecture is an excellent candidate for the yearly battery rotation recommend in many of my writings. At each annual inspection of the airplane, put a new battery in the main battery location and rotate the old main battery into the auxiliary battery location. This means that the main battery with the heaviest duties under alternator out conditions is always less than a year old. The battery in the aux position is always less than two years old.

The only practical alternative to the yearly game of musical batteries is to do periodic battery capacity checks as described in the chapter on batteries. Batteries for electrically dependent airplanes should be checked (1) every 6 months, and (2) after every episode of total battery discharge. Replacement should be determined by the battery's ability to sustain essential electrical loads for duration of fuel aboard.

During alternator out operations, one shuts opens both battery contactors and closes the E-bus alternate feed switch.

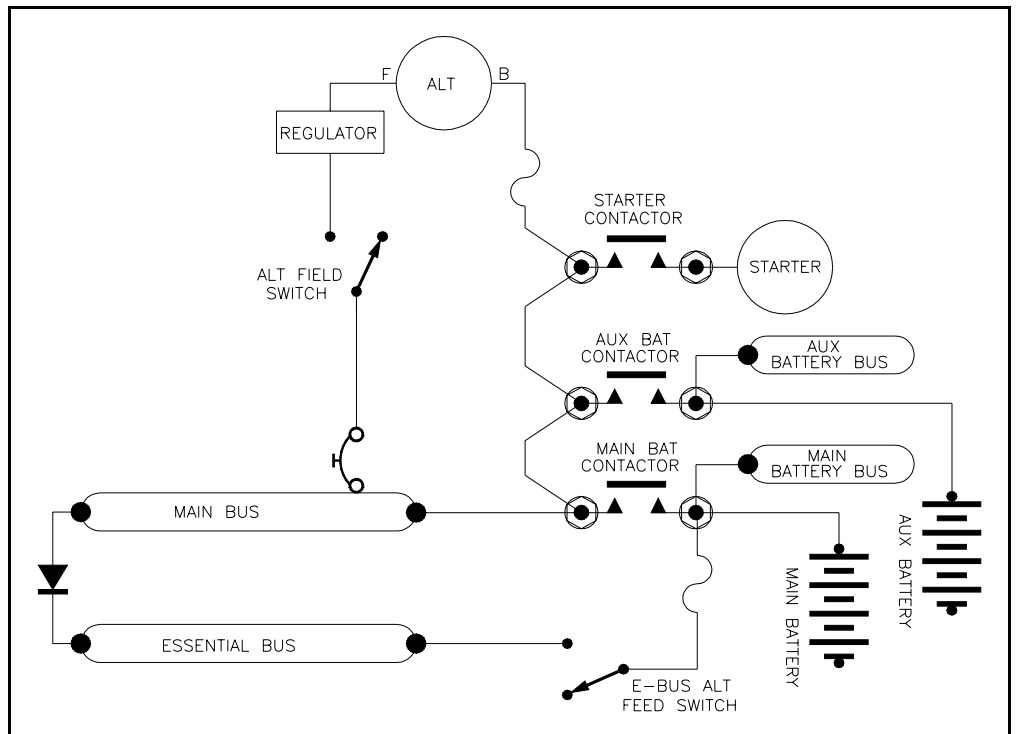


Figure 17-6. Dual Battery Installation

One might even consider shutting off the engine loads on the main battery and using only the aux battery to sustain engine operations for the remainder of the flight. Once the airport is in sight, one may close the battery contactors and use whatever energy is left to run things like landing lights.

### Adding an Auxiliary Alternator with auto-switching. . . .

There's yet a third way to add a second engine driven power source to an airplane as illustrated in Figure 17-7. In this instance, the auxiliary alternator is connected in parallel with the main alternator. However, the regulator setpoint for the aux alternator is approximately 1 volt below normal bus voltage.

In normal flight, both alternators are ON but the aux alternator goes to sleep because its regulator thinks that the bus voltage is too high and drives the aux alternator field voltage to zero. If the main alternator fails to support ship's loads, the bus voltage sags waking up the auxiliary alternator. B&C provides a special regulator for this application. Instead of a builtin low bus voltage warning light, the warning circuitry is configured to annunciate the aux alternator's wake-up call by illuminating an "AUX ALT LOADED" light. A hall effect sensor supplied with this regulator watches the aux alternator output load and causes the AUX ALT LOADED lamp to flash if ship's loads exceed the alternator's rated output of 20A. The pilot needs only to reduce system loads on the bus until the light stops flashing.

This system has been STC'd onto the A-36 and C-210 aircraft and is offered as a production option on the A-36 and by Mooney aircraft. I offer this system as the easiest way to add a second engine driven power source to an existing design.

Many of you are probably wondering when we'll get around to discussing hardware. After all, if you want reliability, you'll want really high quality parts . . . right? Well, there's nothing wrong with high quality parts, certainly one may expect a high dollar part built to government specifications to last longer than the automotive parts store equivalent. But

how does longevity figure into reliability? Obviously, reliability is not hurt if every part you use can be expected to last longer than you plan to keep the airplane. If parts selection was the only reliability factor, the task would be easy. But what about wires, components with complex internals like radios, terminals, nuts and screws and unanticipated damage? What about your personal understanding of the system and options for how it may be operated? Most people's notion of reliability is based on things not breaking. I've suggested in many writings that flight system reliability is driven most strongly by system architecture and the operator's knowledge of how to use it. It's much easier to plan for ways to work around occasional breakage than to depend on every the ability of every part to last for as long as we need it.

### Doing the Unthinkable - Replacing Parts Before They Break!

Spam-can drivers almost never replace a part simply because it had been in service long enough. I say almost never because some parts are routinely replaced before they become unserviceable. How about tires? We've already discussed the notion of replacing a battery when its capacity falls below some optimal value. Of course oil and oil filters

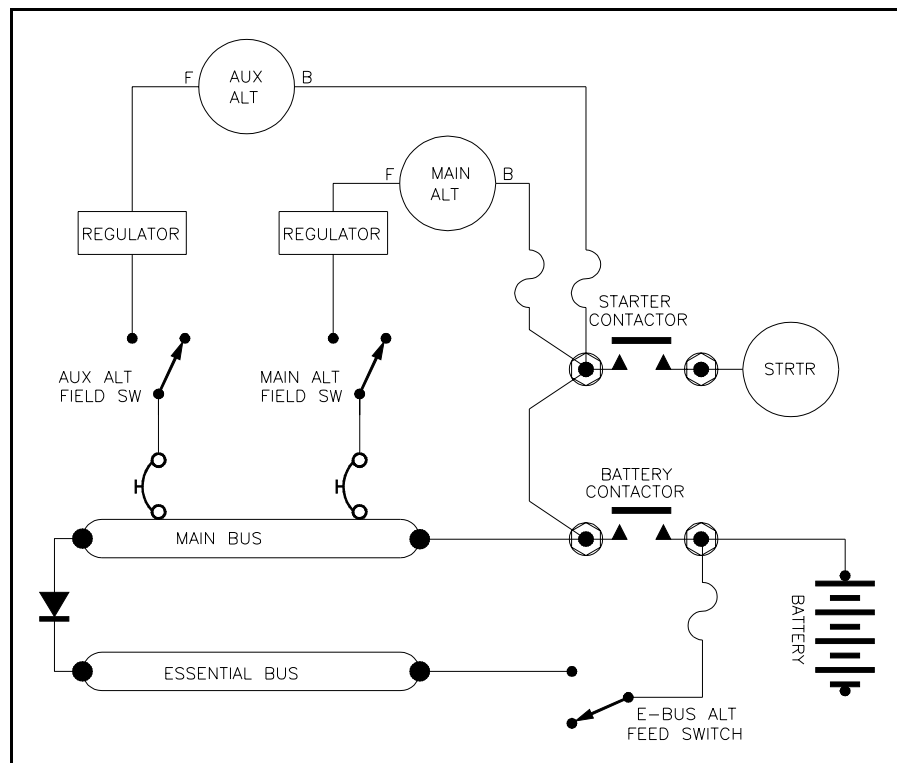


Figure 17-8 Auxiliary Alternator with Autoswitching.

get routine changes before they stop lubricating . . . how about things like switches? Perhaps a fuse block has become corroded in the Florida salt air, how about spending a \$40 and an hour's time to install a new one? If one of your switches has failed and they've been in place for 5-10 years, how about replacing ALL the switches? A horrible thing to contemplate when switches cost \$20-40 each and a high dollar mechanic has to do the job. But suppose you can sit in the pilot's seat of your RV with a nut driver and for less than \$40 and thirty minutes of work, you can have ALL new switches? How do you think this maintenance philosophy would influence the probability of in-flight failure of periodically renewed, high wear components?

### Putting it all Together . . .

Now it's time to apply what we know to select an electrical system that fits your airplane and the way you intend to use it. Figure 17-1 illustrates the way 95% of all production single engine airplanes are wired. I've suggested that pilot Gomez's story would have read much differently had his airplane been wired differently. The majority of our builders will find the architecture in Figure 17-2 adequate to their needs. If pilot Gomez's airplane had received the simple modification to provide minimal lighting, primary navigation and rudimentary flight instrument power from an alternate feed to the battery, his story would have not be very exciting. Turn the essential bus alternate feed switch ON, battery/alternator master switch OFF and continue flying the airplane to a comfortable arrival. Of course, we're assuming that the FBO who rented the airplane replaces batteries in their rental fleet when their capacity drops below useful levels . . . yeah, right.

First, let's talk about Figure 17-5, the mother of all electrical systems. The only reason that you'd want to consider this architecture is if you have an electrically dependent and power hungry navigation and instrumentation system. I've had several Lancair and Glasair builders go for the whole enchilada with glass cockpit, three axis autopilot and electrically dependent systems instrumentation. I assume that pilots of these airplanes plan lots of IFR travel that might include long legs over poor landing conditions . . . like lands between LA and Wichita, or even oceans. If your sky chariot is destined for such duty, by all means, study Figure 17-5. In spite of it's apparent complexity, this system doesn't have to be heavy. There are 3 pound batteries on the horizon that will crank an engine. Two of these batteries in a dual-alternator/dual-battery installation would perform quite well. Obviously, batteries this small cannot boast much capacity . . . indeed, a pair of such batteries would total only 5 ampere-hours . . . when NEW. You'd certainly want to team these products with exemplary alternators . . . which is not

difficult to do. With small batteries, a ground power jack is a necessity. You just wouldn't want to run airframe accessories without having the engine running or ground power plugged in. The point is that technology exists to replace the old Prestolite pig starters, heavy antiquated generators and alternators and flooded batteries with components having a TOTAL weight that is less than the battery we took out. All of these benefits come with levels of system reliability that will probably never be available to our spam-can driving brethren.

The architecture of Figure 17-2 lends itself to orderly upgrade to either a second battery (Figure 17-6) or an aux alternator (Figures 17-4 and 17-8). The compelling reason for upgrading to dual batteries is when both magnetos have been replaced with electronic ignition systems. If you don't plan to have a vacuum system and want dual electronic ignition, then putting an auxiliary alternator on the vacuum pump pad makes the most sense and you can stay with a single battery. B&C alternators have demonstrated fleet failure rates better than 0.5 per 100,000 flight hours . . . an 8-amp auxiliary alternator is about 5x the price of an 17 a.h. auxiliary battery but it's 1/4 the weight.

If you subscribe to our suggestion for yearly swap around of dual batteries, then the cost of an 8-amp aux alternator takes 5 years to break even with the cost of batteries and you'll carry less weight. Further, two engine driven power sources (with reputations equal to or better than B&C alternators ) allow you to rationally consider running a single battery longer. I would be comfortable with battery replacement based only on load testing for cranking ability irrespective of capacity if I had two good alternators.

If you're going to have gyros, then you have to make the vacuum versus electric decision. Electric gyros are more expensive than vacuum devices. They're about the same weight. A vacuum system is about 10 pounds installed, an 8-amp aux alternator is about 5 pounds installed. A vacuum system has quite a few more parts to install and maintain. Finally, wires are easier to install and work around than hoses. As an initial cost savings to get your project air-worthy, consider punching a hole for a DG but put a cover over it and initially install the attitude gyro only. GPS gives you excellent course data. A digital compass is another excellent source of magnetic heading information. I'll suggest that the airplane can be flown quite handily with an attitude indicator and alternative sources for heading/course data.

An autopilot or even just a wing-leveler installation offers a compelling reason for going all-electric. Loss of a single alternator may force you to abandon a valuable pilot assistant

for part (if not all) of the remaining portion of the flight. A second alternator allows you to run a continuous load of 8 amps while saving the battery for heavier, end of flight duties like showing lots of lights, lowering flaps/gear, etc. 8 amps will support minimal E-bus and a light autopilot load quite nicely. Waves of the future are washing over vacuum systems and I am not sad to see them go. I'd take a single, modern alternator over TWO vacuum pumps for securing my future as a pilot any day. Adding a second alternator of any size makes it a no contest decision.

To recap the basic tenants of system reliability:

- The absolute quality of parts has little bearing on system reliability . . . even the BEST parts can break. The best parts can be rendered incapable of operation due to errors in installation or weakness in associated components. For example, what is the value of controlling your landing light with a \$100 switch when you KNOW the lamp is going to barf in 10-20 hours? There are thousands of parts on single engine airplanes that have been shaken, baked, spec'd, conformity controlled, PMA'd, STC'd, TSO'd, ad-nauseam. Does that mean the part will never break? Of course not . . . airplane parts break every day. If airplane parts never broke, FBO repair shops would be out of business . . . As experimental airplane builders and pilots we have better options for development and maintenance of a comfortable flying machine.
- Develop a considered preventative maintenance plan that rotates out aged parts. Batteries in particular need to be replaced LONG before they fail get your engine started.
- Develop simple alternatives for dealing with individual component failures. A cockpit crew on an L-1011 flew a perfectly good airplane full of folks into the Florida swamp when they became preoccupied with troubleshooting a gear-down indicator light . . . One might say the cause of that crash was failure of a lightbulb. More rational analysis suggests an inability of the crew to deal simply with a simple failure. Plan your own cockpit activities to never attempt diagnostics and/or remedies in flight.
- If there are equipment items that you depend on for comfortable completion of flight, have backups for those items. Hand held COMM, GPS and even VOR radios are readily available and less expensive than their panel mounted counterparts. Because they run on internal batteries, they are

totally independent of problems originating in the aircraft's electrical system.

- 99% of single engine airplanes are wired per Figure 17-1, I've illustrated numerous options to improve upon certified aviation's carved-in-stone shortcomings. Do some considered planning on the architecture that best fits your needs. Further, take comfort in knowing that should your needs change or you find that the first pass at a design falls short of your needs, you can FIX IT with a more useful configuration without having to seek blessings from ANYONE..

**Nuckolls' first law of airplane systems design sez:** "Things break"

**The second:** "Systems shall be designed so that when things break, no immediate hazard is created."

**The third:** "Things needed for comfortable termination of flight requires backup or special consideration to insure operation and availability"

**The forth:** "Upgrading the quality, reliability, longevity, or capability of a part shall be because you're tired of replacing it or want some new feature, not because it damned near got you killed."

I often tell my readers they're building the best airplanes to have ever flown. I explain by noting that people who work on assembly lines simply work a job. They may have special training for the task but by-in-large, if something doesn't fit exactly right, they're strongly motivated to "bend it a little" until it does. If something breaks, it's not uncommon for a group of his supervisors to conference to see how to minimize the time and costs of pushing the airplane on down the assembly line.

You folks WORRY a lot about everything. You generally don't act until you've got the necessary advice and knowledge to do it right. If you mess it up, the parts come out and you do it over. By-in-large, amateur built airplanes have the benefits of care and consideration for doing a good job that factory built ships will never enjoy.

Finally, if any of you have the pleasure of meeting pilot Gomez, congratulate him on his skills and ability to deal successfully with a situation that was stacked against him. Show him your home-built project and explain the value for having total control of your destiny. He may well have a special appreciation for the benefits. Who knows, he might even order up his own kit.