TRENDS IN AEROSPACE POWER DISTRIBUTION

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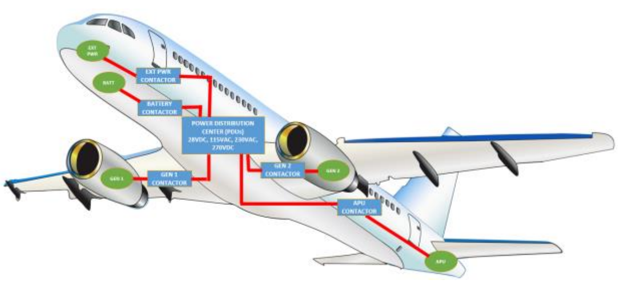
Electromechanical contactors have long been the product of choice for aerospace power systems designers. In a large commercial or military aircraft, contactors are used to control the different power sources, including engine-driven generators, auxiliary power units, batteries, external power, and ram air turbines. Power systems must not only accommodate the routine needs of flight, but also offer redundant backup power and emergency power. Contactors are electrically controlled devices that use a low-power magnetic coil drive actuator to switch higher currents powering loads such as galleys, fuel pumps, or cargo equipment. They also provide power to secondary distribution boxes feeding nearly every load used in flight, from in-seat power to in-flight entertainment systems. TE Connectivity is one of the world's largest manufacturers of aerospace rated power contactors and relays for 28VDC, 115/230VAC application. These range in current ratings from 1-1000 amps.



[Figure 1 | Contactors in use in typical Aircraft Power Distribution Networks]

Size, Weight, and Power Consumption (SWaP) are Critical

In aerospace and similar applications, designers are concerned with reducing SWaP—size, weight, and power consumption. Space is always at a premium, and weight savings translate into better fuel economy, longer flight times, and larger loads. Similarly, lowering power consumption throughout the power generation and distribution system can save weight and space. Considering a large commercial jet may contain 100 or more high-power contactors in the power distribution system, saving even 0.1 amp in control power for each device can be significant in overall power dissipation. Less power dissipation allows smaller power sources. Midrange relays technical requirements are detailed in MIL-PRF-83536. They are used for secondary load distribution and offer multiple poles and form C (changeover) contact configurations. These are lightweight, compact, and highly reliable for use in the most demanding aerospace environments.

[Figure 2 | TE Electromechanical Power Contactors and Distribution Relays]

The Challenges of Higher Voltages in Aerospace Power Systems

Switching high currents and voltages over many years of aircraft service can be a challenge for power contactors. Thermal stress and normal contact arcing during switching can wear both contactors and interconnects. The switching energy common with opening of the main contacts may be less severe with conventional 115VAC systems: by definition, the voltage/current drops to zero each cycle, lessening the magnitude of spikes and allowing clearing them more quickly. At 230VAC, however, the spacing of open contacts must be increased to help eliminate arcing re-strike as voltage escalates after current zero.

In modern aerospace AC power systems, frequency is no longer fixed at 400 Hz. It varies from 350 to 800 Hz depending on engine speed. Designers of both contactors and power panels must carefully evaluate the effects that this wide frequency range has on device life and thermal performance.

The adoption of 270 VDC and 540 VDC, first into the military and now commercial aviation has forced dramatic design changes in power contactors. Existing contactor designs are not suited for high-voltage switching because of their inability to generate adequate arc voltage for interruption. To overcome these physical limitations, the contactor design must rely on such methods as arc splitting plates, runners, blow-out magnets, and better internal switching atmospheres.

[Figure 3 | TE Electromechanical HVDC Power Contactors]

For many years, aerospace power contactors have largely been all-or-nothing ON/OFF contactors with little added intelligence and circuit protection. One of the most important trends today for military and aerospace contactors is building in more electronic intelligence to provide protection against abnormal events and to detect systems faults. These features become even more important as power systems have elevated voltages like high-voltage direct current (HVDC).

Reducing Contactor Power Consumption

One of the first areas where electronic controls were added to contactors was for economizing circuits to reduce coil power consumption. All electromechanical contactors contain a magnetic actuator which requires considerably more power to start the actuator's motion to close the contacts than is required to hold them closed. For example, it may take 5 amps to actuate a contactor, but less than 1 amp to maintain the ON state—an 80 percent reduction in power can be realized via improved coil control. This results in less heat generation and less stress to the device or power distribution panel.

Two common methods used to economize power consumption are multiple coils and pulse-width modulation (PWM).

In early economized contactor designs, the actual transfer of power from pickup to hold windings was accomplished using mechanical limit switches. Once the actuator has transferred through most of its travel, a switch is tripped to reduce power. Limit switches have proven problematic for several reasons. The adjustment can be extremely critical for proper long-term contactor performance since the switch can be actuated too early or too late in the cycle. Since the switch turns off the high-power winding coincidental to main contact closure, it may cause increased contact bouncing or chatter.

With the integration of electronic coil controls, the transfer timing of the coil power is no longer tied to actuator motion and a limit switch. It becomes possible to ensure the contact sets have fully transferred and are in a stable closed position before initiating the coil transfer. By thus controlling the timing of the transfer, reliability is significantly improved.

PWM uses ON-OFF coil pulses of different durations—or duty cycles—to control the average current delivered to a coil. PWM has the advantage of tolerating a wider range of voltage levels but may cause radiated noise if not properly filtered. PWM also has the ability to adjust the duty cycle during abnormal operating voltage. During low battery conditions, the duty cycle ON time is increased to effectively create a constant current source for the contactor.

Overload Current Protection

A common issue with aerospace power systems is the danger of overloads. Electrical faults can occur not only in the load equipment but also within an aircraft's wiring and electrical power distribution network. This has been well studied relative to aging aircraft and the effects of long-term environmental exposure on insulation systems. Protection includes detecting under-voltage at the generator, monitoring running current levels, and detecting leakage current.

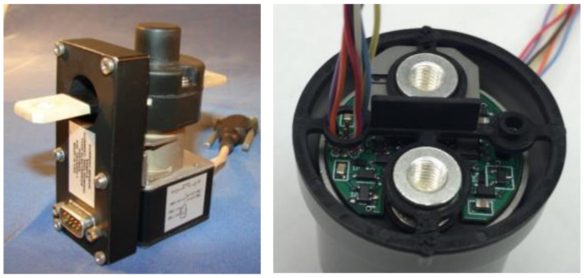
Many existing applications still rely on bimetal-based thermal circuit breakers. These devices are low-cost and can also be used as a full disconnect for troubleshooting. However, they are not suited for very high currents, have limited trip curve accuracy, and have no BIT features to ensure they will perform properly when needed. To overcome these deficiencies, electronic sensing is often integrated into the power contactors.

Electronic sensing provides more reliable sensing of overcurrents. These devices can provide at least twice the trip curve accuracy over conventional thermal circuit breakers. Electronic sensors can also be exercised through built-in tests to simulate fault events to ensure they will perform as expected if a system fault occurs.

The first requirement for electronic overload protection is a method to accurately monitor running current through the contactor. The simplest method is to use a precision resistor as a shunt and simply measure the voltage across it. The method is very accurate but can generate considerable heat in high-current contactors. It also is less than desirable for mixing control circuits and 120 V/240 V sense lines for overall systems integrity.

A second method for monitoring current is a current transformer (CT). The magnetic field created by the feed-through current establishes a secondary current in the CT. The current is proportional but is much lower. A typical ratio of current to CT current is 500:1. CTs are simple to apply and accurate but can be heavy in the case of open-loop sensors or complex in closed-loop designs.

Hall-effect sensors are another common method of measuring the magnetic field created by the current. Hall-effect elements have a voltage output level based upon exposure to a magnetic field. This field is most commonly focused across the Hall-effect sensor using a flux ring or collector surrounding the contactor's bus bar or output feeder. Modern Hall-effect sensors are programmable for output voltage and linearity and can allow bidirectional current sensing and AC sensing. Figure 4 shows a Hall-effect sensor integrated alongside a TE 28VDC contactor or directly integrated into a 600VDC design.



[Figure 4 | TE Hall-effect sensors are flexible and accurate.]

Advantages of the Hall-effect sensor are:

- Isolation between primary and secondary circuits
- Works with direct or alternating current
- High accuracy
- High dynamic performance
- High overload capacities
- High reliability

Regardless of sensor type, supporting electronics are required to collect information from these sensors and make decisions on system configuration. In certain instances, the integrated electronics only communicate running conditions to other aircraft systems. This information can be very useful in decision-making for load shedding if a power source is lost. Aircraft loads are prioritized for criticality so that noncritical convenience loads are depowered in order to maintain flight-essential and other critical loads.

In addition to communicating circuit conditions, contactors with integrated sensing electronics can react independently to overload fault conditions. This allows fast trip and lockout as fast as 10ms. The level of fault protection for ***smart contactors***—i.e., those with electronic sensing—can even be adjusted by the user or specific application position to tailor protection for each individual load. Such adjustments can be accomplished through connector pin programming, DIP switches, external resistor additions, or software coding. This also allows the smart contactor to be reconfigured if the application warrants changes.

Additional Fault Detection and Protection

While sensing overcurrents is generally the prime task required of a smart contactor, other faults can be sensed. These include:

- Loss of phase and phase rotation
- Differential feeder fault
- Ground fault
- Arc fault detection

Phase Faults

To protect motors, fans, and other devices using three-phase power, phases must remain synchronized to ensure the proper delivery of power. Phase faults stress the operated devices, shortening their lifetime, causing improper operation, and even bringing catastrophic failure. The two main phase faults are loss of phase and improper phase rotation. Both result in uneven, unbalanced delivery in power. When one of the phases is lost, delivered power is diminished since only two phases are delivering power. Phase rotation error occurs when the phases are not properly synchronized at 120 degrees of separation.

The same techniques used to monitor current for overloads can be used to detect phase sequence problems. By sensing and comparing current levels on each phase, any difference can be detected.

Leakage Current Fault Protection

Sensing leakage currents and protecting against differential faults involves multiple current sensors along a length of wiring. Outputs of the sensors are compared to detect faults. Ground fault detection is a specialized protection scheme using only one common sensor to ensure all passed current is also returned from the load without leakage. This detection means has become commonplace on aircraft fuel pump applications to reduce risk for fuel vapor ignition.

Differential feeder fault protection is common in the aerospace industry. This is usually a high threshold protection to validate no current leakage on large-diameter power feeders. A typical setup includes a sensor at or within the power generator and a second one at the main line contactor. If the sensed currents are different, a fault has occurred.

Ground faults can be monitored in two ways. One way is to check for current in the ground plane. The second is to use the information provided by the phase sensors. The sum of all three phases should be zero. If it does not sum to zero, a fault exists in the wiring or load.

Arc Fault Detection

Arc fault detection is becoming more commonplace in circuit breakers and secondary solid-state power controllers (SSPCs). It has been demonstrated that existing protective devices are ineffective against sputtering arc faults. While current levels may not increase enough to trigger a hard fault, arc faults can generate unacceptable heat levels. Parallel arcing faults may ultimately progress to full overcurrent faults, while series arcs resulting from broken conductors or loose device terminals could generate tremendous heat even though the overall current is well below the circuit breaker trip curve. Detecting arc faults and even locating distances to a wiring fault is an emerging area for smart contactors.

Beyond Electromechanical Contactors

While solid-state relays are common, the application of power semiconductors to contactors is relatively new. MOSFETs can replace the power contacts, with the obvious advantage in improved reliability relative to no moving parts. Solid-state power devices can extend the switching life of a contactor. Power contacts are subject to wear from both the mechanical mating and the effects of arcing. As contacts wear, the increased resistance across the connection means increased heat generation and end of life failures.

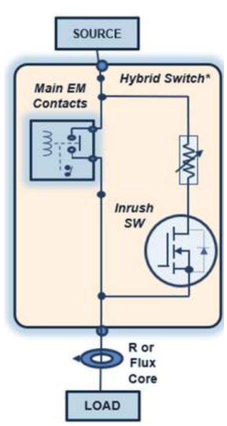
Solid-state relays require additional thermal management versus hard contact designs. While the absence of mechanical parts makes solid-state designs very reliable, the main failure mechanism now becomes heat. The devices must be protected from overheating. Beyond heat sink thermal management, multiple power transistors can be applied in parallel to keep currents well below the maximum rated levels. For aerospace applications, transistors are de-rated at 15 to 20 percent of datasheet current-carrying rating in order to manage thermal performance effectively. An accurate fault current specification is more critical in solid-state design as compared to conventional EM contactors.

Solving the "Hot-Switching" Challenge

The challenge of "hot-switching" contactors became further elevated as the aircraft industry pushed toward the concept of more electric aircraft (MEA). This trend started with conversion of on-board hydraulic systems to electric actuators and now even propulsion systems are moving to electric operation in the case of eVTOL aircraft. Entire new classes of HVDC architectures are being developed that may extend to 6KVDC. Clearly components designed for 270VDC are not suitable to these new demands. For most high-current HVDC loads such as propulsion a motor controller is in use and upstream contactor hot-switching life is not critical (turns on at minimal current). However, it is critical that the contactor can open under load in the rare event of a controller, motor, or feeder failure. The challenge designers face in HVDC is finding the proper balance in specifying hot-switching endurance versus actual application needs. The size, weight, and cost penalty for overspecification can be significant for HVDC architectures. There is good news, however, considering there are now solutions to these issues found using hybrid contactors and high-power full solid-state power controllers (SSPC).

Hybrid Design

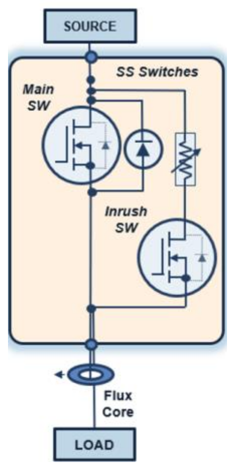
A hybrid contactor design combines the low ON resistance advantage for an electromechanical contactor with non-arcing power switching of power electronics. This eliminates a significant wear-out mechanism within the contactor and allows contact material selections based more on low on-resistance and less on hot-switch durability. Hybrids have been demonstrated to increase hot switching life for HVDC contactor from a few hundred cycles into the many thousands of operations. Naturally, hybrid contactors are more complex and often more costly than conventional EM contactors, but for applications requiring many cycles of hot-switching, this is an attractive solution.



[Figure 5 | Hybrid Power Contactor]

Solid-State Power Controllers (SSPCs)

SSPCs combine the capabilities of a full solid-state power switch along with various monitoring and communications features. At a minimum, an SSPC has an integrated overcurrent trip curve to protect the wiring/interconnects as well as the load in the event of excessive current draw or short circuit. SPPCs can also communicate for command and status over a vehicle data bus to improve system reliability and availability. SSPC can be configured remotely for behavior under unique conditions or for specific loads. High voltage SSPCs as offered by TE Connectivity can also be provided with a built-in pre-charge feature. These products are often powering non-linear loads and motor controllers with largely capacitive inputs. The SSPC can handle the pre-charge in a timely fashion while reducing surge currents on power up.



[Figure 6 | TE Solid-State Power Controllers]

From Sensing to Prediction

Microcontroller-based control allows more information about the state of the contactor or SSPC to be gathered and analyzed. This information can be used to go beyond basic trip circuits in response to faults. It is one thing to sense a fault and shut down a component. More useful is to monitor operation over time to identify trends and changes. This allows intelligent prediction of problems and flexible responses.

Current and voltage levels can provide real-time insight into the health of the contactor and of the overall aircraft electrical system. Information on running currents, temperature, and number of cycles can be used to predict the life of the contactor. Operating the contactor at lower current and/or voltage levels can significantly increase the number of switching cycles.

The collected data can also be used to monitor the system. For example, current draw after initial power up reflects inrush currents to motors or pumps, yielding insight into bearing wear. The same information can indicate the need for lubrication or other maintenance. Changes over time in sensor data can also indicate faults in the wiring system.

Comparing initial operations to changes over time is fundamental to understanding and predicting problems. While the output from a single device can yield useful data, information from multiple devices and from other sensors in the wiring system can be combined into "big picture" analysis and prediction since it allows comparison of conditions throughout the system.

Aerospace Trends: Power Distribution Panels in Integrated Assemblies

As contactors become more sophisticated, they also become more complex. Many users are opting for custom-designed, application-specific power panels; an example of one designed and built by TE is shown in Figure 7, as a plug-and-play solution to power management and distribution. These panels contain not only relays and contactors, but also the control electronics to provide advanced monitoring and control capabilities.

[Figure 7 | Custom power distribution panels provide an engineered solution for power distribution management.]

Contactor design has evolved. Smart contactors, hybrids, and SSPCs can now provide enhanced and increasingly intelligent monitoring of conditions. Because they play a central role in power distribution and management, the information obtained from sensors can be used not only for fault management, but also to monitor and analyze the health of the power system. In modern aircraft, analysis of trends is a key to ensuring long-term reliability and the ability to maintain systems in a timely and efficient manner.

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