

Power systems and requirements for integration of smart structures into aircraft

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ABSTRACT

Electrical power distribution for recently developed smart actuators becomes an important air-vehicle challenge if projected smart actuation benefits are to be met. Among the items under development are variable shape inlets and control surfaces that utilize shape memory alloys (SMA); full span, chord-wise and span-wise contouring trailing control surfaces that use SMA or piezoelectric materials for actuation; and other strain-based actuators for buffet load alleviation, flutter suppression and flow control. At first glance, such technologies afford overall vehicle performance improvement, however, integration system impacts have yet to be determined or quantified. Power systems to support smart structures initiatives are the focus of the current paper. The paper has been organized into five main topics for further discussion: (1) air-vehicle power system architectures – standard and advanced distribution concepts for actuators, (2) smart wing actuator power requirements and results – highlighting wind tunnel power measurements from shape memory alloy and piezoelectric ultrasonic motor actuated control surfaces and different dynamic pressure and angle of attack; (3) vehicle electromagnetic effects (EME) issues, (4) power supply design considerations for smart actuators – featuring the aircraft power and actuator interface, and (5) summary and conclusions.

Keywords: power requirements for smart actuation, hingeless control surfaces, air vehicle subsystem architectures, EME effects, piezoelectric actuation, power conditioners.

1. AIR-VEHICLE POWER SUBSYSTEM ARCHITECTURES

Any manifestation of a new smart actuation system must deal with many aircraft integration subsystem and environmental requirement issues. An important consideration will be interfacing the smart structure flight control actuation with the resident power system architecture for the target vehicle. An air-vehicle conventional power subsystem architecture approach for today's tactical aircraft is illustrated in Figure 1.

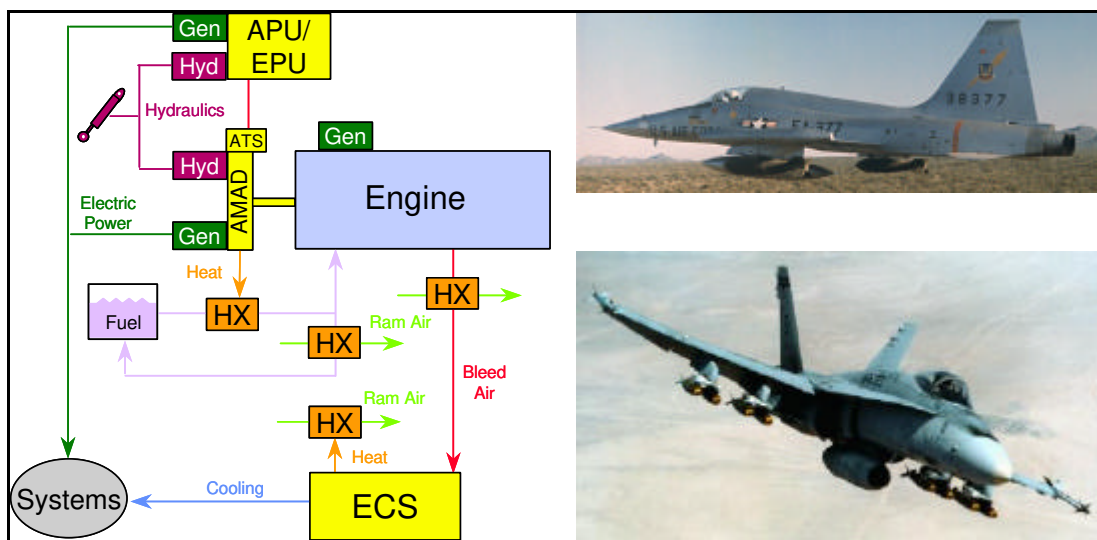


Figure 1. Traditional Air Vehicle Architecture

Such systems are driven by redundancy and fault tolerance requirements (in particular the ability to supply uninterrupted power) as well as cost, weight, power quality and electromagnetic compatibility (EMI). Figure 1 shows the engine driving twin generators coupled through the airframe mounted accessory drive (AMAD) that feeds 115 volts AC conforming to the classic power quality specification of MIL-STD-704¹. The upper loop in the diagram provides emergency power through an air turbine starter (ATS) that restarts the auxiliary power unit (APU) generator after an emergency loss of engine at high altitude, or continuous ground power when the aircraft is stationary or parked. In the event of engine flame out at high altitude, the emergency power unit (EPU) must provide enough power to maintain continuous operation of the flight controls before APU recovery at low altitude. Thus, the flight control surfaces are essentially “on duty” continuously. Bleed air is provided to the environmental system and some of the extra heat is rejected to the fuel.

For redundancy, the engine spins two generators to provide the requisite electrical power, usually in the 50 to 100 kW range for a modern tactical aircraft, and a lower power (e.g. 2 to 3 kW) transformer rectifier provides 28 VDC to electrical components. It is important to stress that any new electrically powered actuation system that would require non-standard power levels (e.g., in this case differing from 115 VAC or 28 VDC) would have to incorporate its own power supply. Such additional complications should be considered in the overall benefits study that the new technology offers.

Looking ahead considerably more complicated power system architectures are being evaluated and tested. Figure 2 shows an architecture from Northrop Grumman Corporation’s recently completed Power Management and Distribution System for a More-Electric Aircraft (MADMEL)² whose goal was to replace hydraulic, pneumatic, and mechanical power actuation with electrical equivalent components for an overall reduction in maintenance costs. Elimination of a centralized hydraulic system provides the major benefit in terms of life-cycle-costs. The MADMEL architecture (Figure 2) is a hybrid system supplying 115 VAC @ 400 Hz and 28 VDC as above, but most importantly 270 VDC which is likely to become standard in future aircraft applications.

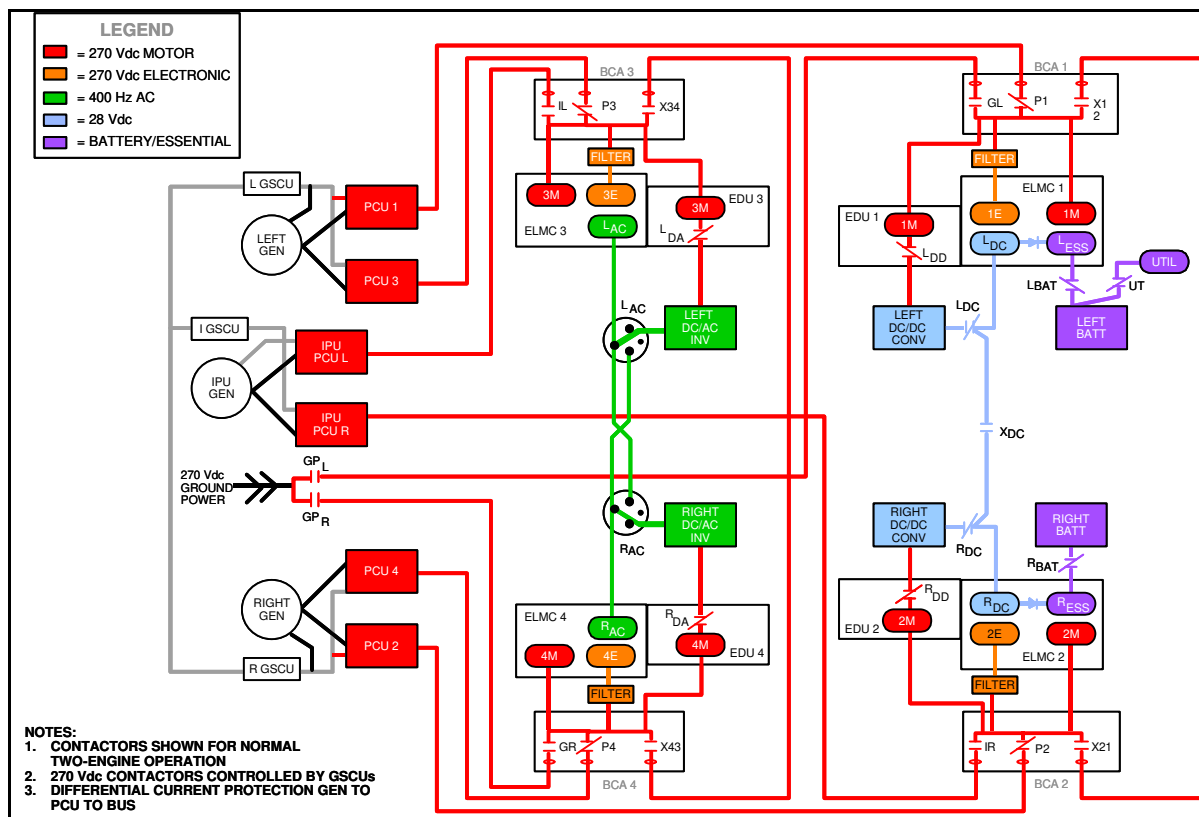


Figure 2. MADMEL Power System Architecture

The primary distributed power is 270 VDC configured in three channels, two main engine and one integrated power unit (IPU). The ground power is also 270 VDC in each channel is derived by rectifying variable frequency AC from the three phase generator in a power control unit (PCU). The PCU output is then segregated into a motor and electronic bus for distribution into the aircraft. The motor bus has less stringent noise and power quality (e.g. not completely conforming to MIL-STD-704E/461D) requirements and is more tolerant of conducted noise emissions than the electronic bus that supplies flight critical and sensitive avionics such as the flight control, weapon control and mission computers. It is possible that smart actuation components could take advantage of the relaxed bus specifications in some future implementation, with an architecture similar to MADMEL, but it cannot be guaranteed. Each of the three channels contains a generator and system control unit (GSCU), which control the generator, PCU, and two channel diagnostics bus control assemblies (BCAs). The GSCU also performs channel diagnostics, communicates system status to the other GSCUs over discrete data lines, and communicates system status to the VMS over a 1553 data bus. Further details of MADMEL may be found in reference 1.

Figure 3 depicts yet another power system architecture that is representative of a set up that may be used for future unmanned vehicles. The essential difference from the foregoing is that a thermal management energy module (T/EMM) is really a combination of all three of the former ECS, APU and EPU elements and can operate the rotating machinery from the engine bleed air and/or burn fuel. For completeness, other salient features of this architecture include: 1) 270 VDC power system conforming to MIL-STD-704E; 2) Off-the-shelf YF-22 class DC to DC converter to provide 28 VDC; 3) silver-zinc maintenance free battery for back up; 4) oil-less and gearless air cycle techniques utilizing engine bleed air to provide the cooling and electrical power; 5) high reactance permanent magnet brush less generator used to provide electrical power; 6) fault tolerant, triplex architecture for flight critical loads; and 7) inverters available to convert 270 VDC to 155 VAC.

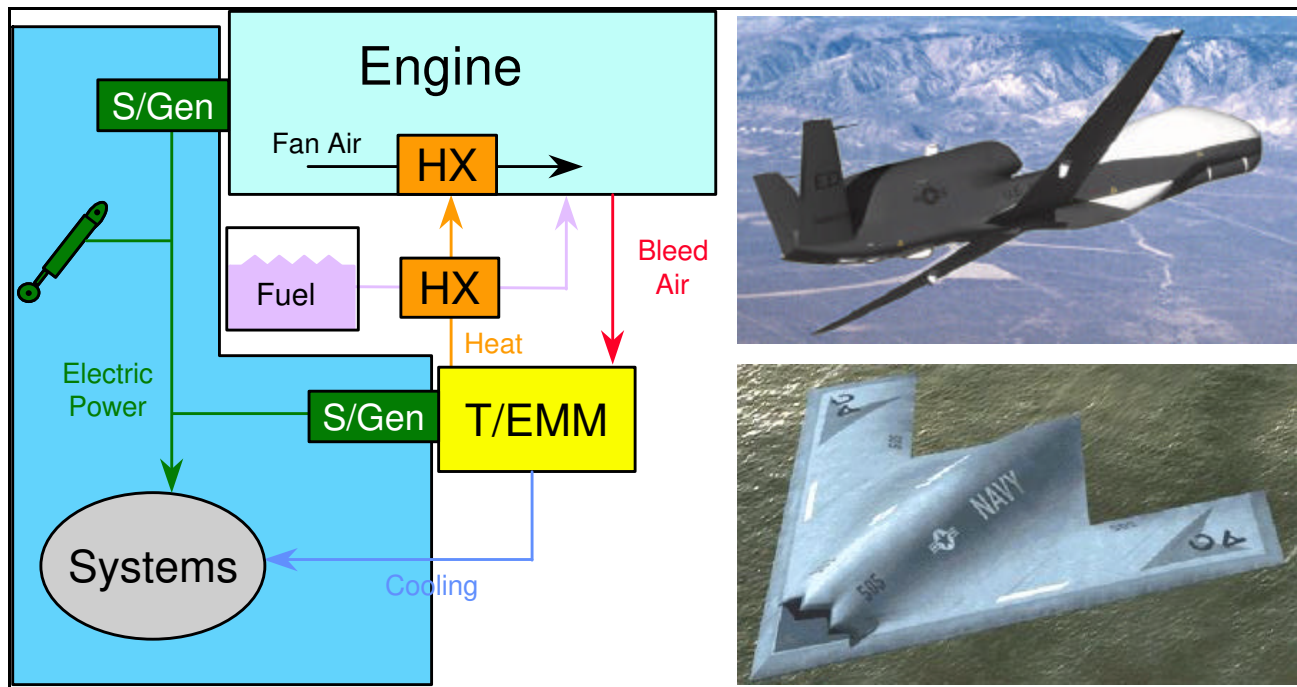


Figure 3. Example State-of-the-Art Architecture for Unmanned Air Vehicles

It should be apparent from the foregoing discussion that any future smart structure control surface implementation will have to develop its own interface power supply and power conditioning derived most likely from a 270 VDC bus, 115/200 Volt, 400 Hz alternating current supply. Switch mode regulated inverters or converters will likely have to be employed to buffer the actuation electronics from the aircraft bus and to mitigate power quality and EMI constraints placed by the aircraft on the integrated smart components. This will be further discussed in the following sections.

2. SMART WING ACTUATOR POWER REQUIREMENTS AND RESULTS

During the recently completed DARPA smart wing programs^{3,4,5} a variety of new actuation concepts, focused toward Unmanned Air Vehicle (UAV) applications, were investigated and evaluated. The earlier smart wing phase I effort was focused on technology validation and proof-of-concept rather power supply development and airframe integration issues. It was a sufficient challenge to validate for the first time with wind tunnel data that hingeless control surfaces could be operated in a smoothly continuous manner and provide benefits over conventional wing surface actuation methods using smart materials. Power supply issues could not be fully addressed at the first technology development step. Nevertheless, power and thermal issues were scoped in gross terms using rather "brute force joule heating" techniques with large heavy off the shelf power supplies and thick conductors to provide the necessary power and high current demands for shape memory alloy (SMA) actuation.

On the smart wing program, it was proven for the first time that the wing could be twisted using a torque tube heated by a nickel chromium wire and cooled by shop air. The torque tube actuation relies on the high strain that can be achieved when a metal transforms from its martensitic to austenitic state. In simple terms, the actuator may be described as a hollow cylindrical piece of shape memory alloy that is trained to provide 10 to 15 degrees of twist at anywhere between five hundred to thirty five hundred inch-pounds of applied torque. It was also demonstrated that leading and trailing edge wing control surfaces could be actuated using SMA material. For, this application, an altogether different configuration using linear shape memory wires was used to actuate compliant control surfaces. A series of SMA wires can be configured along a control surface and produce actuation by heating the wires in a particular manner and sequence. As in the torque tube case, a shape memory wire has the useful property of producing a large strain when undergoing a phase change. Wires are arranged to operate in an antagonistic fashion. Essentially, wires configured on the top surface pull against lower surface wires, whose length are controlled by temperature. To contour a surface downwards, wires on the bottom of the surface are hotter than those in the top configuration. Further details of these techniques may be found in references 3, 4, and 5.

Figure 4 illustrates the voltage and power requirements to actuate these concepts and for both cases the methods present considerable airframe integration challenges. While DC power supplies do not usually constitute RF radiation problems and slow changes will not likely couple transients, high current and low voltages if non-standard (e.g., 6-7 A @ 31 to 34 volts) might pose aircraft integration challenges. Step down conversion circuitry would have to be added if the air-vehicle source supply rails are at 270 VDC and there could be a significant weight impact if long conductor lengths are required to distribute power from a centralized bus on the vehicle. Note also that even the sustaining voltage (Figure 4) for the SMA wire is quite high at around 2 Amperes. There are also some cooling issues that would have to be dealt with using whatever thermal management and ECS system would be employed by the air-vehicle platform. For instance, passive local cooling approaches would have to be considered or traded against centralized liquid or air-cooling, or direct fuel cooling from local wing structure might be appropriate.

The next significant technology breakthrough in terms of smart actuation came during demonstration of the smart wing phase II second wind tunnel series of tests. Here, it was demonstrated that span-wise movement of the control surfaces could be accomplished at significant rates and deflections to rival hinged conventional surfaces for maneuverability. Up to 15 degrees deflection of the wing surface was achieved by a segmented flap arrangement driven by a new kind of piezoelectric/ultrasonic actuator. Figure 5 compares the peak values for total power consumption for a uniform shaped control surface driven by SMA wires and the non-uniform "bird wing" and "bathtub" span-wise configurations enabled by the new technology ultrasonic motor (SPL-801) for similar deflection angles. Taking shape variation into account, it can be deduced that while the peak power for the two cases are similar the SMA requires considerably more energy. Approximately 20 times more energy is required and dissipated for the SMA case, which moves the surface much more slowly than the ultrasonic actuation method. Furthermore there is a residual sustaining requirement for the SMA to keep the surface deflected which is not necessary for the SPL-901 that remains locked when the power is removed.

- Smart Wing Phase 1 and Phase 2
 - Torque Tube Heated Via Ni-chrome Wire and Cooled Using Shop Air
 - Leading and Trailing Edge Control Surfaces Directly Heated (Joule Heating)
- Both Systems Used DC Power Supplies to Actuate

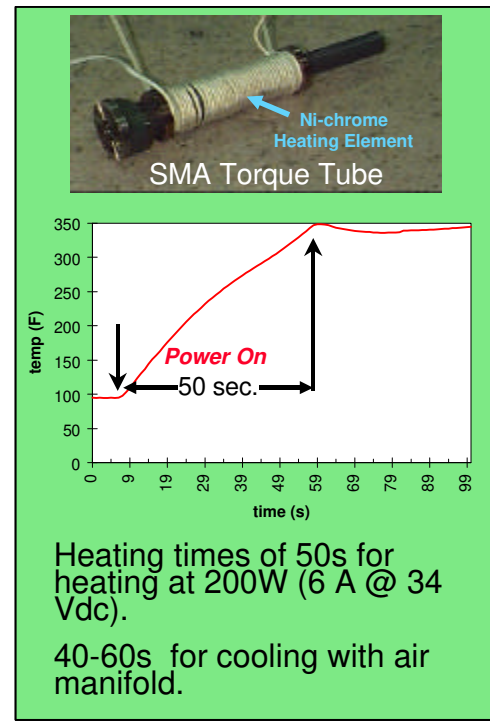
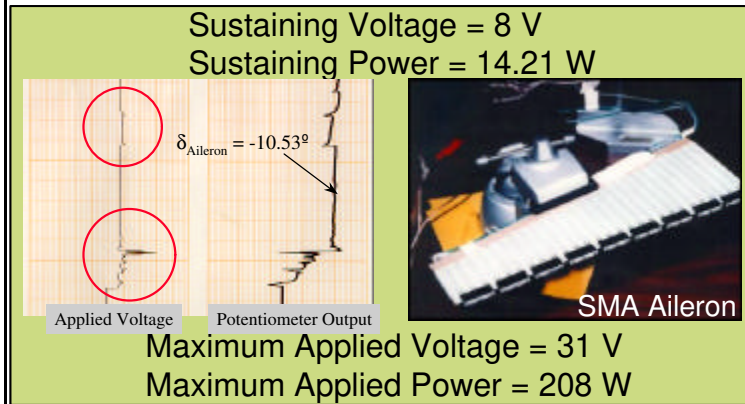
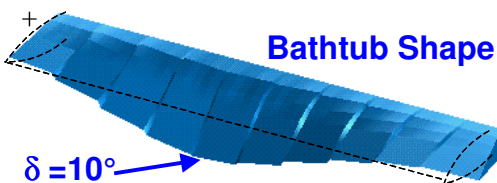
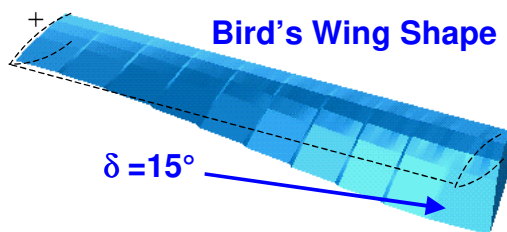
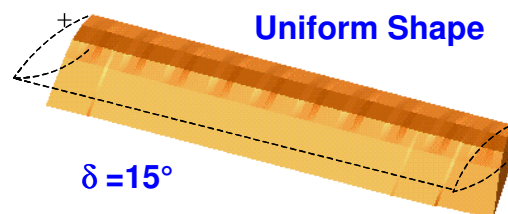


Figure 4. Smart Wing Phase I Actuation and Power Requirements

Test Conditions: Air, Mach=0.8, Q=150 psf, AOA=6°



Control Surface Power Comparison

	SPL-801	SMA
Peak Actuating Power (Energy)	920 Watts (190 J)	1440 Watts (5800 J)
Peak Holding Power (Total)	0 Watts	720 Watts

Total Peak Power (Energy) Required By Ultrasonic Motors: 660 Watts (132 J)

Total Peak Power (Energy) Required By Ultrasonic Motors: 560 Watts (115 J)

Figure 5. Smart Wing Phase II Actuation and Power Requirements

Such comparisons performed under limited test conditions with neither method optimized for power supply design would seem at face value to greatly favor the ultrasonic driven actuator method. On the other hand, the SPL-801 does introduce another complexity since it was fed from 12 VDC @ 13A and needed an inverter to step up to 250 V rms at 35 kHz. Thus, this method introduces a switching frequency noise component that can conductively couple on to the aircraft power bus and/or radiate large fields that become a susceptibility problem for other sensitive aircraft equipment. A further complexity is also introduced by the capacitive nature of the piezoelectric materials employed by the ultrasonic method. This is discussed in detail in Section 4.

Until more research and development is directed toward power supply design optimization and minimization, a recurring issue for smart material based actuators will continue to be the volume, weight, and power requirements of the supporting electronics. Figure 6 shows some of the off-the-shelf items that were purchased to support the smart wing program wind tunnel activity. Note that the volume and weight were in the 20 lbs and 1,440 cubic inches region for both the SMA and Piezoelectric motor driven power supplies and the SPL-801 controller already reaped the advantage of a certain degree of miniaturization. Naturally, the electronics would have to be repackaged for the actual air-vehicle application and further miniaturization and optimization is possible. Switching power supplies offer opportunity for volume and weight reduction if the additional noise they are likely to introduce into the aircraft power bus can be minimized or reduced to an acceptable level.

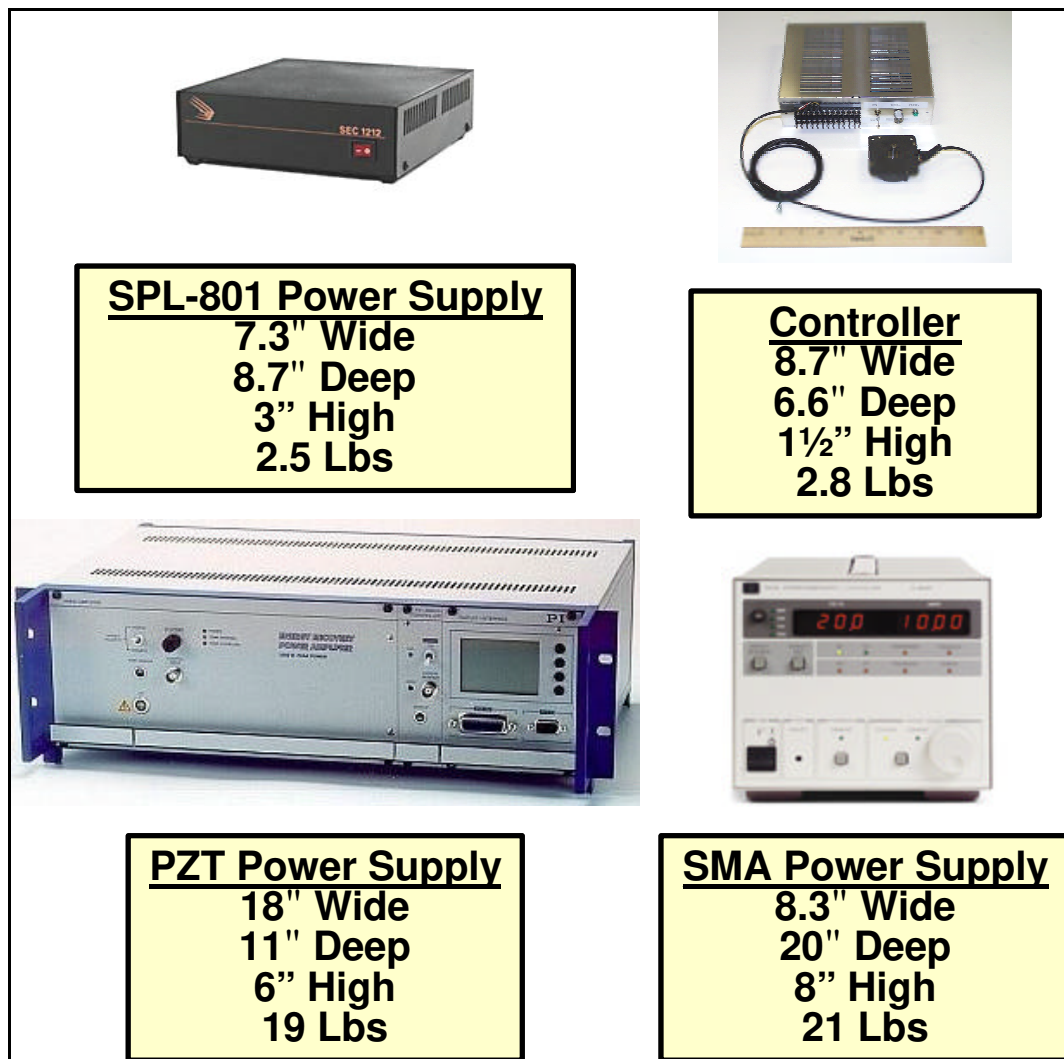


Figure 6. Off-the Shelf Power Supplies Employed on the Smart Wing Program

3. VEHICLE ELECTROMAGNETIC EFFECTS (EME) ISSUES

It is appropriate to review some of the critical air-vehicle electromagnetic effects (EME) integration issues for any new actuation system or component that would be integrated into the wing structure. Specifically, the requirements cover electromagnetic interference (EMI), electromagnetic pulse (EMP), electrostatic discharge (ESD) and lightning. While recent manifestations of the MIL standards (e.g., MIL-STD-461E) offer ways to ease compliance, traditionally the standards have been stringent. EME may be broadly categorized as external – those requirements that the aircraft environment imposes on the installed component, and internal – the intrasystem requirements that impose constraints on how components may be affected by other aircraft equipment. How the installed system may disrupt otherwise functional avionics equipment is perhaps an even more critical issue. Installations in the wing associated with flight control surfaces are usually considered flight critical from a safety standpoint. Grounding, shielding, and power bus issues will need to be solved as well as lightning susceptibility wing leading and trailing edges qualify as zone 1A candidates*. For the external EME effects, Figure 7 summarizes key EME vehicle requirements with comments and some guidance on how the effects may be mitigated for a real aircraft smart actuation installation.

EME REQUIREMENT	MAJOR COUPLING AND ACTUATOR SUSCEPTIBILITY MODE	COMMENTS AND MITIGATION TECHNIQUE
Susceptibility of Installed System to External Radiated Fields and Electromagnetic Discharge		
<ul style="list-style-type: none"> MIL-STD-461, RS03 - Radiated Susceptibility <ul style="list-style-type: none"> 200 V/m, 14 kHz to 40 GHz Electromagnetic Pulse (EMP) <ul style="list-style-type: none"> Use 50,000 V/m Continuously from 10 kHz to 630 kHz 414 V/m, -20 dB/Decade from 630 kHz to 76 MHz 239 V/m, -40 dB/Decade from 76 MHz to 100 MHz Electrostatic Discharge <ul style="list-style-type: none"> Static charge field requirement ~ Flat at 140 dB/μV/m from 10 to 100 kHz ~ 20 dB/Decade Roll off from 100 kHz to 1 GHz 	<ul style="list-style-type: none"> Electromagnetic Induction coupling to wires and circuitry Transient Coupling to smart actuator wiring and circuitry could cause malfunction EMP dominates below 10 kHz whereas RS03 prevails above Minimize High electrostatic voltage concentrations that couple unwanted V & I Trailing edge critical for static discharge - conductive link required for control surfaces 	<ul style="list-style-type: none"> RS03 applicable for All major weapon system air-vehicle, Navy carrier deck most severe Protect by conductive shielding and/or bypassing interference signal by filtering Charges must be drained to prevent damage and noise coupling to smart electronics Use bleed paths Avoid - abrupt surface resistivity transitions, composite mold lines
Lightning Susceptibility – MIL-STD-1757, Lightning Qualification Test Techniques for Aerospace Vehicles		
<ul style="list-style-type: none"> MIL-STD-1757, Direct Attachment Requirements <ul style="list-style-type: none"> Zone 1 — 200, 000 Amps for 500 μsecs Zone 2 — 2,000 Amps for 5 milsec Zone 3 — 8 to 200 Amps for 1 second duration MIL-STD-1757, Indirect Effects — Estimated field intensities at 250 meters from cloud to cloud discharge: <ul style="list-style-type: none"> 1 Million V/m transient at 10 kHz 50,000 V/m at 630 kHz 200 V/m at 17 MHz 	<ul style="list-style-type: none"> LE and TE control surfaces are in most susceptible lightning zone 1B - high prob. of attachment stroke re-strike and flash hang on. Lightning current will seek the most conductive path through the smart actuator hardware and circuitry Indirect similar to EMP 	<ul style="list-style-type: none"> Prob. of Attachment versus altitude varies 1 in 5k, 100K, and 1M hours for terrain clearance, 20Kft, 30Kft respectively - 40Kft, unknown Component survivability rather than performance interruption is goal Protect by design similar to RS03 but much more emphasis on material (e.g. conductive paints) methods

Figure 7 External EME Smart Actuation Vehicle Integration Requirements

Aside from the external EME levied on the smart actuator, there is also a host of other intrasystem EMI requirements that must be met which apply at the component level before the equipment is installed in the vehicle. These are the classic MIL-STD-461⁶ requirements that govern: (1) unwanted electromagnetic emissions that may be conducted back into the aircraft bus or radiated from the equipment while in operation, and (2) conducted and radiated susceptibility requirements that the complete subsystem must live with from other operational aircraft installed equipment. Such requirements are indicated in the family tree of Figure 8 and are a subject in their own right. However, the key

* Zone 1A an aircraft location per MIL-1757 where installed equipment is susceptible to the most severe lightning condition, namely an attachment current of 200,000 amps for 500 microseconds.

requirements that any potential designer should take account of in developing smart actuation power supplies to the next level are these:

1. MIL-STD-461 D CE01, CE03, and CE07 that govern the steady state and transient conducted emissions over the frequency regime from 30 Hz and apply at the actuator subsystem power lead interface (see Figure 8).
2. MIL-STD-461D RE02, RE03 and RE07 that govern the steady state, spurious and harmonic radiated emissions over the 14 kHz to 40 GHz frequency regime and apply to the field strengths radiated from the equipment subsystem at 1 meter distant.

The designer should also consult the later version of the standard – MIL-STD-461E appendices that provide excellent guidelines for interpreting the specifications, however, version E is relatively new and will not necessarily be invoked even for future platforms. Other considerations aside from constraints imposed on the design by the MIL standards are all the usual aspects of grounding, bonding and shielding required to address EMI during the vehicle installation. Problems associated with ground loops and common mode impedance coupling were experienced and had to be solved during the wind tunnel testing (Section 2) using off the shelf power supply and instrumentation. The challenge will likely be an order of magnitude greater for the vehicle installation.

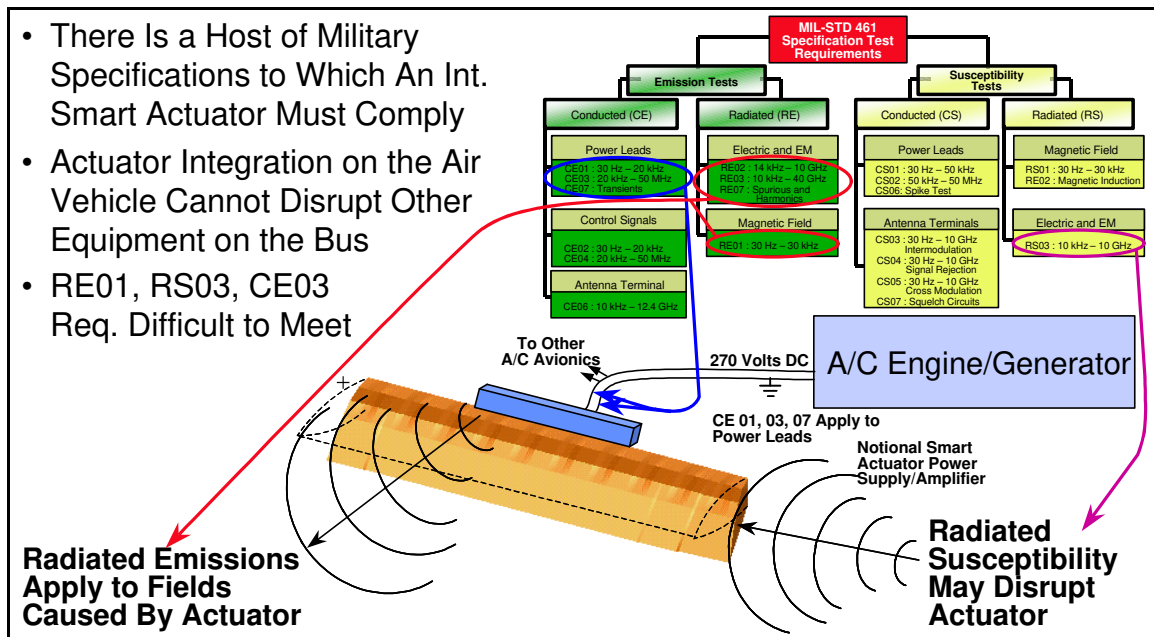


Figure 8. Applicable MIL-STD-461 Intra-system Component Level EMI Requirements

Apart from the RS03 requirement, which has been highlighted in Figure 7, it is felt that the equipment susceptibility requirements are less critical, since the vehicle smart actuator installation is viewed as a source of EMI rather than victim. The EME requirements have been emphasized more in this paper than the MIL-STD-704E requirements that govern power quality, since they are less well known to equipment designers and are frequently neglected.

4. POWER SUPPLY DESIGN CONSIDERATIONS FOR SMART ACTUATORS

It should be apparent, by now, that power supply design for smart actuators remains a challenge that will be heavily driven by military standards if the final goal is to transition the technology to military air vehicles. Let's revisit some of the previous work done in this area by Virginia Tech and make some suggestions for future challenges.

It would seem from Section 1 that the most likely power bus architecture will require smart actuator operation from a 270 VDC bus. Since piezoelectric actuation requires a sinusoidal alternating drive signal, some DC-to-AC inverter is necessary to operate from the bus. Figure 9 shows one such arrangement initially applied by Virginia Tech⁷ to solve the buffet load alleviation problem for a vertical tail aircraft application. A piezoelectric stack was used to suppress the unwanted movement of the surface, but in principle the design is very similar to the smart actuator power supply requirement discussed in this paper. Due to variations in both the power drive source and load, regulated power flow is necessary for smooth control surface operation. Figure 9 shows a switched inverter bridge connected directly to the supply rails to provide a 270 Volt peak-to-peak signal driving the actuator stack. The stack itself is represented by a large capacitor. A duty cycle controller invokes an inner loop current and outer acceleration controller to keep the AC supply to the actuator well regulated and constant.

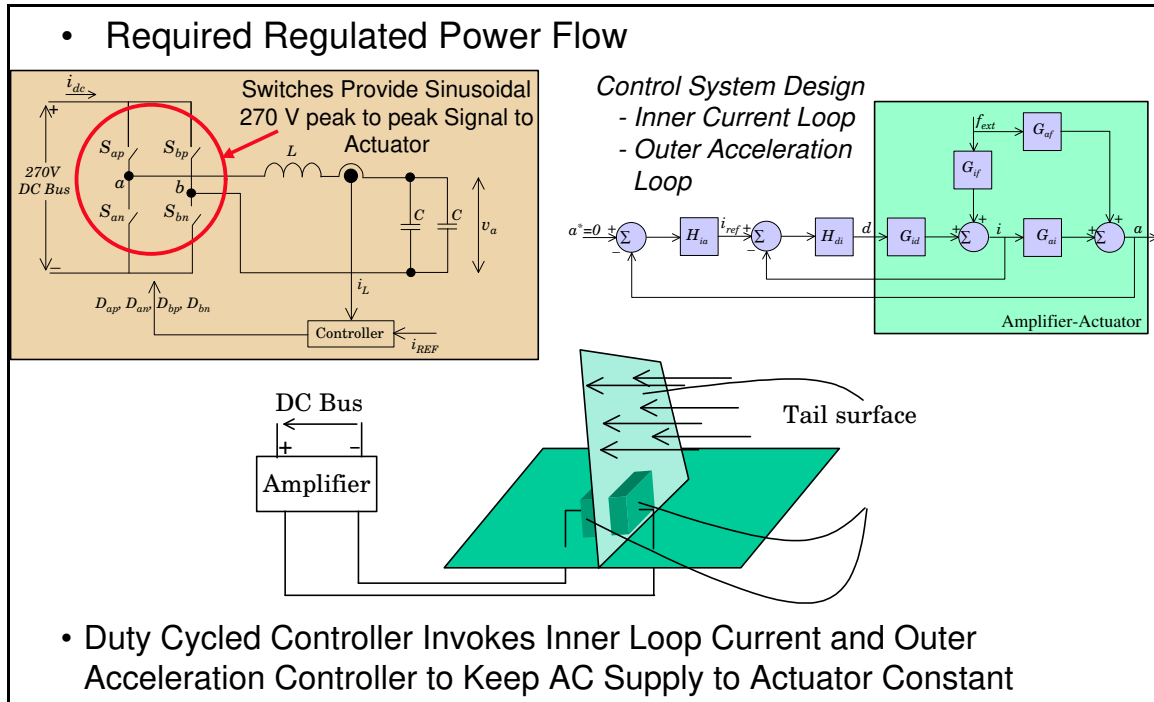


Figure 9. Power Amplifier and Interface Considerations for Smart Actuators

Glossed over so far, though, is the challenge that the piezoelectric actuator stack presents as a very large capacitive load for the power supply designer⁸. The drawback of connecting the power supply interface circuitry directly to the bus is that the regenerative power of the stack actuator will couple transients and a large ripple component on the aircraft bus. And we know from earlier discussions that aircraft power buses are controlled by stringent military standards — in particular by MIL-STD-704D and MIL-STD-461, CEO3. The left-hand side of Figure 10 shows an ideal voltage generator and 3-phase rectifier producing 270 VDC coupled through the amplifier to the actuator load. The box in the figure labeled "other loads" represents a parallel connection to the input terminals of all the other aircraft equipment on the bus that may number from a few tens for a UAV scale class aircraft to over 200 equipment boxes for a large bomber such as a B-2. The unwanted voltage ripple components from the reactive power would circulate between the amplifier/actuator subsystem causing efficiency problems and will pollute all equipment connected to the bus at a frequency determined by the stack actuator switching. Typically, this might be anywhere between 20 Hz to 35 kHz depending on actuator requirements.

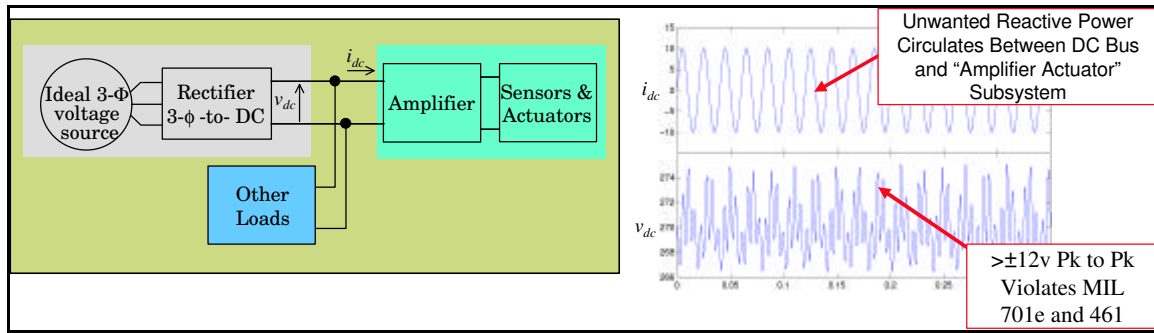


Figure 10. Power Bus Impact for a Capacitive Piezoelectric Stack Actuator Load

For the particular case that Virginia Tech modeled, using nominal power conditions, a voltage of 12 volts peak-to-peak was predicted for the magnitude of the noise signal. Coincidentally, this happens to be the power quality limit of MIL-704 for all of the aircraft equipment connected to the bus in total, not just the contribution from one emitter. The latest version of MIL-STD-461E, CE03 conducted emissions limits the requirements to be 100 times (or 20 dB) more stringent than this number for a single bus equipment, thus providing a key design goal for power supply equipment designers.

Bi-directional power flow from the smart actuator installation should therefore be avoided, if possible, to isolate the aircraft bus from unwanted noise effects. Noise cancellation techniques can be used to circumvent this problem. A possible solution is to use a bus conditioner as illustrated in Figure 11. The active bus conditioner senses the harmonic (or pulsating) power required by the load and supplies the appropriate power. Any method involving circuitry that constitutes an actively controlled storage device sourcing and sinking energy to the bus could be employed. Virginia Tech and other researchers have proven the theoretical feasibility of the method. However, practical designs where additional weight and cost penalties for the added electronic components used to solve the regenerative power problem have yet to be determined.

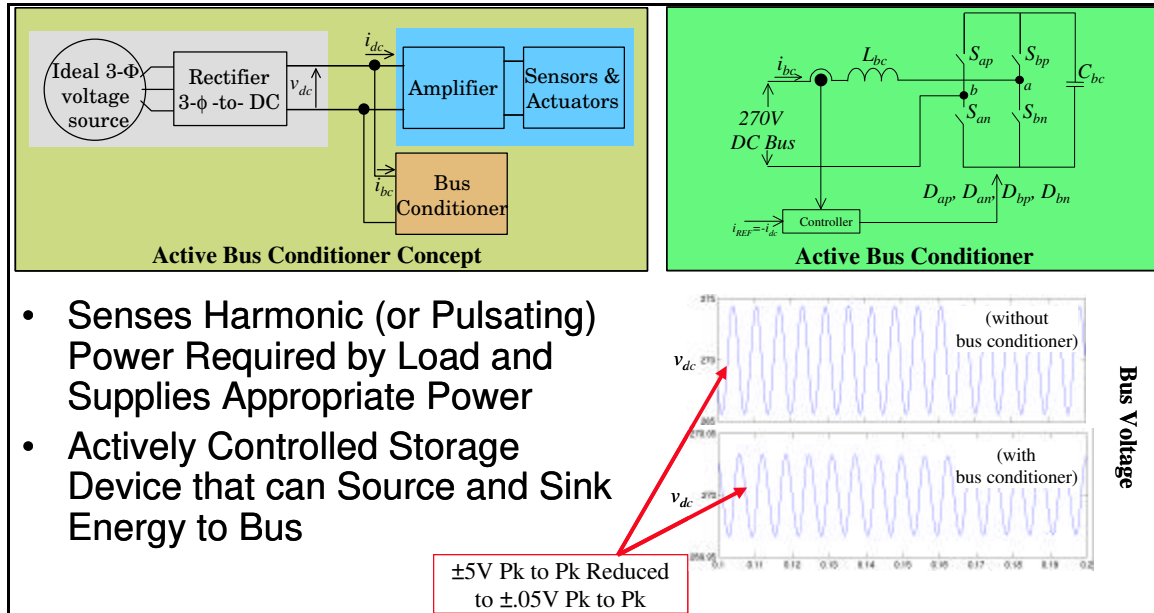


Figure 11. Solutions to Reactive Power Bus Connection

Since it is almost certain that additional bus conditioner hardware will be necessary, the next phase of the smart actuator development might also incorporate new features for reasonable cost and complexity. For example, a step-up inverter might be used to provide a more efficient drive voltage for stack actuation. Some research has shown that a thousand

volts peak to peak might be more suitable than 270 volts. This would require a step up transformer of 4 to 1. This concept is illustrated in Figure 12, which shows an inverter bridge that could be duty ratio controlled as in Figure 9, but with a step up transformer across the arms of the bridge to provide both the needed voltage translation. The transformer also has the added advantage of providing isolation between the source and load. This would, of course, present an aggressive challenge for the power supply designer in addition to switched charged control and hybrid strategies⁸ for combating the capacitive piezoelectric load that still remain largely (to the author's knowledge) unsolved.

MIL-STD-704E governs the new 270 VDC power quality standards and mandates that connected equipment should operate without malfunction for transient conditions. A voltage drop of 26% must be met for the negative transient condition, and 22% voltage surge needs to be accommodated for the positive transient condition. Both transient conditions can last up to 50 milliseconds. This means that passive input filtering will be necessary since the active controller cannot instantaneously respond to a fast edged transient.

Combinations of passive and active filtering techniques, strategically matched to mitigate this problem, have been used with some success in the past⁹. Briefly, the method is to use a choke "of the right size" (a few microhenries) placed at the inverter input to limit the speed of the incoming transient but large enough to provide sufficient "breathing space" for the active loop to respond. The switch mode regulator closed loop gain characteristics has to be safely rolled off at 6 dB per octave (rule of thumb) to prevent instabilities due to the well know "negative impedance characteristic" phenomena. The closed loop gain of the switch mode regulator must be sufficient (20 to 30 dB) to reduce the transient to a safe level. This is one method, but other approaches to incorporating an input filter buffer should be investigated.

Trade studies could be performed for the choice of switching device (e.g., transistor, thyristor, power MOSFETS, silicon carbide device, etc.) and frequency operation. The advantage of higher switching frequencies in power supply design – such as reduced component weight and faster response times and regulation capabilities for the active control loop, would have to be traded against the upper frequency limit for piezoelectric stacks. Such trades and optimization in actuator design performance still need to be addressed in the next phase of technology assessment.

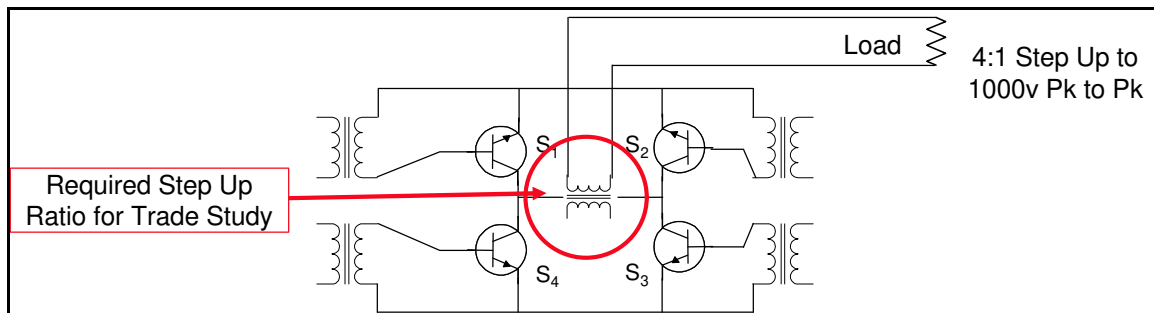


Figure 12. Inverter Design Enhancements

5. SUMMARY AND CONCLUSIONS

Traditional and future air-vehicle power system architectures were reviewed for a variety of platforms to determine the most likely power bus supply rails and interface requirements for a smart actuator installation. These are the traditional 115 /200 VAC at 400 Hz AC and 28 VDC supplies, and the emergent 270 VDC bus governed by the later versions of MIL-STD-704 and MIL-STD-461. It was pointed out that the smart actuator subsystem will almost certainly need to incorporate its own power supply with the necessary step up and step down inverter or converter features depending on the vehicle installation. Power loads recorded during the smart wing program phase I and II were presented to provide specifics for the power supply designer for both cases of low rate SMA flap actuation and high rate piezoelectric driven surfaces with spanwise control. These were 31 V at 208 Watts and 6A @ 34 VDC for the flap and torque tube SMA cases and approximately 1500 watts peak power for the high rate piezoelectric case. Finally, some power supply design considerations for smart actuators were revisited with heavy emphasis on bus interface requirements and piezoelectric capacitive load challenges. Some suggestions to facilitate future smart actuator power supply incorporation into the air-

vehicle bus targeted mainly at 270 VDC applications were also made; however, similar considerations and issues apply to the other power bus sources.

It should be apparent that the smart actuator power supply designer currently immersed in the design challenges of power dissipation, non-linear amplifier behavior and capacitive piezoelectric at the component level must now face a myriad of air-vehicle integration requirements before he is done. The smart wing program has opened the door for innovative concepts such as spanwise control surface deployment, however, some interesting challenges remain for the subsystem designer to accommodate technology transition to a real air-vehicle platform.

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