EXPERIENCE IN MAINTAINING AND OPERATING POWER SUPPLIES USED IN ACCELERATORS

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Abstract

The operation of power supplies providing power to magnets and other devices used to control charged particles in accelerators demands a careful approach to their specification and design. What follows are some practical principles and considerations based on 20 years of operating experience at Fermi National Accelerator Laboratory. Some general principles apply to all equipment where high reliability is the goal Other principles apply more specifically to one of two separate categories depending on the general operating mode of the accelerator. The modes considered are a fixed target or "rapid cycling" mode and a continuous or "collider" mode. There are differences that arise due to the unique requirements placed on the power supplies in each application.

DESIGN AND OPERATING PRINCIPLES

General

An obvious but paramount principle in the design and operation of all equipment is to minimize heat and mechanical vibration. Stated simply: if long term reliability is the goal, heat and vibration are your enemies.

Sensing relay contacts, switches, etc., should use at least 24 V (preferably 40 V) and 20 mA unless you know for sure that the contact you are sensing is of the "dry circuit" type. Vibrations can affect relay contact integrity over time. If response time isn't critical (for example, in the use of klixons for temperature sensing), use lots of filtering.

High current bus connections deserve special attention. Whenever possible, these connections should be welded or brazed. If this is not practical, the connections should utilize conical washers and at least two bolts on each lug. Within high current power supplies it is a good idea, during the commissioning phase, to use thermal imaging to verify that all connections are tight. When the high current connections are exposed or frequently disconnected, particularly in accelerator enclosures, some means of "certifying" the joints should be applied. The system we use consists of installing locking devices with each nut. After completion of joint reconnection, a wire is laced through each locking device and the wire ends are fixed with a seal. Routine tunnel inspections need only to verify that the seal is present to insure that the joint has not been disturbed.

Keep design engineers involved in reliability issues to help solve tricky problems. Weekly meetings with maintenance technicians and engineers to review all failures can be an effective means of maintaining the level of intensity needed to track each and every problem to a satisfactory solution. However, management must realize that this will affect the engineering resources (we estimate 1 equivalent person) available for other projects.

Rapid Cycling Machines

In rapid-cycling applications, the relentless cycling of mechanical and thermal stresses greatly reduces the lifetime of equipment whose design does not specifically take these conditions into account. It has been our experience that just providing a manufacturer with operational waveforms does not ensure the long term (> 3 year) reliability of procured equipment subjected to continuos cycling.

Minimize temperature excursions. This is most important when applied to the solid state power devices used in the equipment. An acceptable level is difficult to determine but our experience indicates that the peak junction temperature of the device should be limited to about 80 °C. Since our maximum water temperature is 40 °C, this results in a maximum of 40 °C temperature cycling.

Minimize mechanical stresses. Our experience is greatest in the magnetic components of a power supply in general, and the main power transformers specifically. Experience has shown that constant pulsing of these components above their rms current levels (but within their rating) greatly diminishes their life. For this reason we have modified our transformer specifications to rate transformer MVA at a level that is about halfway between the expected operating rms and peak levels. We further stress to manufacturers that the transformer should be "mechanically" designed on the basis of the peak pulse value.

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Collider Machines

During collider operation, a single nuisance trip in a piece of equipment can result in the loss of many hours of experimental physics. The time lost is typically the time required to recover operation, plus the time required to establish a new beam store (about 12 hours at Fermilab).

Long term flawless operation of each piece of equipment must be emphasized. A conservative design approach that results in building many circuits for power supply protection can be counterproductive if those circuits are prone to give an occasional false trip.

During power supply design, all fault responses should be evaluated to determine whether a "turn-on inhibit" or a "ramp inhibit" would be sufficient rather than a trip. For example, if the system uses redundant power supplies or UPS's that utilize solid state line transfer switches, inhibiting the next ramp may be a sufficient response to a failure that allows continued operation.

DESIGN CONSIDERATIONS

1. Minimize maximum operating temperatures. This is a restatement of the above general principle to emphasize its importance. For solid state power devices, the maximum operating junction temperature should be limited to 80 °C.
2. The system design should allow for the easy connection of transient recorders. Key signals should be buffered and accessible for connection.
3. For complex systems, where budgets permit, build in transient recording from the start.
4. All trip monitors and turn-off commands should be latched to facilitate troubleshooting. When a limited number of remote read backs are available, have the detailed information available locally and use summary bits for remote readout.
5. All trip and fault monitors should be heavily filtered if speed is not essential.
6. Our experience has shown that analog panel current meters with overcurrent trip capability have reliability problems. Use a solid-state substitute.
7. When selecting or specifying water hoses and fittings, consideration should be given to the type of water cooling used. For example, we have found that for LCW systems it is best to avoid brass whenever possible, especially in quick-disconnects and ball-valves. For small diameter hoses, we prefer a nylon hose (Imperial Eastman NYLO-SEAL). For larger hoses we use either Parker PARFLEX Series 518b nonconductive or Goodyear ORTEC.
8. Standardize designs when possible. This can be difficult to do when attempting to procure a custom designed power supply under the competitive bidding process. But even then one can specify the use of standard subsystems within the power supply. This is particularly important for complex control subsystems such as high-precision current regulation electronics and phase-controlled SCR firing circuits.
9. Avoid electrical contact problems. These problems can be particularly insidious because they may not show up for 5 years.
    - Avoid sockets. Solder IC leads whenever possible.
    - Use good quality connectors.
    - Spot check crimp connections.
10. To reduce nuisance trips due to noise, use good quality line filters on all low voltage equipment connected to the AC mains. If possible, low voltage power supplies should incorporate grounded electrostatic shields between the primary and secondary power transformer windings.
11. Derate low voltage power supplies and DC/DC converters by a factor of two. Verify that the manufacturer of these items has a good reputation for reliable equipment.
12. Avoid high-impedance analog circuits when possible. When forced to use high impedance components, apply a moisture resistant coating to them. We have had good experience with Tek Spray FINE-L-KOTE SR, Silicon Conformal Coating.
13. Control equipment environmental conditions. When possible, install equipment in air-conditioned rooms. Monitor the temperature and relative humidity of these rooms and generate control room alarms when limits are exceeded. Watch out for high humidity and sources of high humidity. For example, we developed problems with sensitive quench detection electronics that were eventually traced to air-handling units that drew warm moist air into air-conditioned electronics rooms. Moisture condensing on high impedance resistors caused their values to fluctuate resulting in false trips. Avoid HVAC systems that use outside air for cooling during certain times of the year.

MAINTENANCE CONSIDERATIONS

1. Maintenance technicians should *not* reinstall a piece of hardware into the machine if something wasn't found or fixed in it. If you can't fix it, throw it out and build or buy a new one!
2. Build more spares. This will give technicians more time to troubleshoot equipment with intermittent problems.
3. More elaborate system test facilities should be built to allow effective long-term troubleshooting of equipment with intermittent problems.
4. If a power supply has tripped and there is no obvious failure, a general policy should be to replace some module or component and connect a

transient recorder to the system. If the trip occurs again, enough information may be available to positively identify the problem.

5. If, during equipment commissioning or trouble shooting, the system behaves unpredictably, the personnel involved should take the time to track down the problem. For example, if cycling the breaker in a power supply occasionally causes an erroneous trip in one of the interlock circuits, the source of the noise should be tracked down and eliminated. Such problems have a way of manifesting themselves during normal operation. During collider operation this usually results in a lost store. While it isn't always possible to immediately solve this type of problem, determining the solution should remain a high priority.
6. When troubleshooting a problem or trip, first make hard copies of all pertinent control system status pages; do not rely on memory. If called in from home, ask the machine operators to copy the pages while you are traveling. This should be done even if the pages indicate nothing in particular. In such cases the hard copies will serve as verification of a fault with no signature.
7. Protect systems that use low water flow for cooling. These systems are prone to clog, resulting in water flow or temperature trips. Any time the plant water system is going to be off for repairs or replacement of magnets or other components, low water flow devices should be valved off until the system has been restarted and is operating smoothly. There have been many cases of flow problems from blockages that occur within a short time after the water system has been shut down and restarted. Because the small orifices in these devices are prone to collect contaminants, routine measurements of the flow levels should be performed to early detect possible problems.

CONCLUSIONS

At Fermilab we have been formalizing and implementing the above guidelines for the past 2 years. During this time the Tevatron has operated in Collider mode while the Main Ring has run in a rapid cycle mode creating Pbars for the collider program. We believe the process has started to make a positive effect on the program. Table 1 displays the number of failures that led to lost stores in the Tevatron for various substystems during two different one year periods.

Table 1: Number of Lost Stores in the Tevatron

SYSTEM	6/92 to 6/93	7/94 to 7/95
Quench protection Hardware	21	13 (6)
Main Magnet Power Supplies	3	2
Low Beta Power Supplies	13	10
Other Systems	82	40
Ended Intentionally	184	239
Total Number of Stores	303	315

( ) Indicates additional stores lost due to repeat failures of one particular system.

The process of improving the reliability of the Collider is a tedious one made especially difficult as the age of the machine increases. Major upgrades and preventive maintenance activities to improve reliability are difficult to justify as operating budgets continue to tighten. The principles outlined in this paper have helped us stem the rising number of nuisance trips and equipment failures and maintain a high level of equipment availability.