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TEN YEARS OPERATIONAL EXPERIENCE WITH THE ISR POWER SUPPLIES

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Summary

Performance and reliability improvements have been made to the 300 magnet power supplies, their remote control system and the mains distribution network. With the high beam currents now stacked in the ISR, physics data taking would be degraded if the power supplies only performed to their original specifications. It has been necessary to improve the low frequency noise generated by the power supplies at least two orders of magnitude. Modifications have improved the reliability of the power supplies to the state that it is now rare for a beam to be lost due to a power supply failure. Overall, the results have given longer and cleaner stable beam conditions for the physics programme, improved flexibility of operation and easier maintenance.

Reliability

The level of reliability of a power supply is inherently built in at the design stage and it is difficult and expensive to improve on this. The electronics generally represent less than 10% of a power supply cost, therefore it is uneconomic to use other than good quality components with proven reliability and guaranteed performance so that the electronics is not the critical factor on performance and reliability of a power supply. With the issue of performance specifications and the system of competitive tendering, it has proved difficult to obtain power supplies to the reliability standard that is required for storage ring operation, i.e. not a single malfunction of any one of the 300 ISR power supplies over a period of 5 days. To achieve this level of reliability, improvements have been made from the level of urgent repairs due to catastrophic corrosion of water cooling circuits to the systematic rebuilding of some of the power supplies.

Causes of unreliability

Analysis of the systematic faults in the ISR power supplies showed that the major cause of unreliability was poor engineering, e.g. water circuits that leaked, components that ran too hot, etc. Very few of the reasons really turned out to be the components themselves but how these components were used. For example, thyristors have proved to be more reliable than the fuses used to protect them; interlock circuits give more faults than the items they are supposed to protect, etc. Performance specifications should not be exagerated as this encourages manufacturers to incorporate unnecessary complicated circuitry e.g. a series transistor regulator with its associated water cooling, protection and interlocks; whereas with a slight relaxation of the specification a simpler and more reliable power supply could have been achieved.

Water cooling. A series of 125 small power supplies, cooled using a closed circuit water system with a water/air heat exchanger fan and pump, showed after one year of operation, corrosion to such an extent that the cooling circuit developed leaks. Urgent repairs to copper sleeve the aluminium heat sinks and supply cooling water from the ISR demineralised water system solved the problem. Eventually, these power supplies were remodified to eliminate the problems caused by the mechanical polarity reversal switch, the current measuring shunt, the control loops and again the water cooling circuits. Another series of 70 medium power supplies had severe corrosion problems due to the quality of the cooling water, again the solution was to connect up to the demineralised water system.

Component improvement. Items systematically failing have been replaced e.g. plastic encapsulated semiconductors by metal or ceramic packages, plastic water fittings by stainless steel, overloaded components by correctly rated ones, etc. Some of the modifications originally aimed at improving the performance gave large improvements in reliability. An example is improvements made to the control loops of a series of 48 power supplies with series transistor regulators which could be made, due to the availability of high bandwidth operational amplifiers. In this case the control loops could all be made identical instead of individually adjusted. This eliminated operator intervention, with the consequent removal of PCB's where the connector was unsuitable for repeated manipulation, which when left untouched proved reliable. Also in the same power supplies the passive filter was improved to reduce the ripple thus allowing more margin in the variation of the operating point of the series regulating transistors ensuring that they could accept a mains step of ± 10% and not need regular re-adjustment.

Temperature stabilisation. A large improvement to the reliability of the 80 power supplies located in the main power hall of the ISR was obtained by stabilising the ambient temperature to 20 ± 2°C.

Design of a reliable power supply

Based on the experience obtained, a new series of power supplies was launched in 1974[1] incorporating as a trial the following concepts : natural convection cooling i.e. no water or fans; transformer and choke wound from copper conductor with a Δt measured by resistance of 55°C max. and class E or better insulation; junction temperature of thyristors less than 125°C with an ambient temperature of 40°C and maximum output; the only interlocks being a fast D.C. overload derived from the meter shunt, earth leakage detection by monitoring voltage across 1 ohm earthing resistor, thermostat on transformer and chokes, ripple detection by thermostat on damping resistor of passive filter; separation of electronics from power part to reduce electromagnetic interference and allow the electronics to run cooler; a simple Direct Current Current Transformer (DCCT) of the parallel type with filter for precision current control; and a logical layout giving ease of access from one side only. These power supplies have proved to be extremely reliable in operation and these concepts are now incorporated in all new power supplies.

Problems remaining. There still remains the problem of switching on and off the power supply remotely with a mechanical switch. Considerable investigations have been carried out but with no satisfactory solution. So far the motor driven circuit-breaker with thermal and magnetic overload plus a no-volt coil for fast switch off under interlock operation is the best compromise.

Performance

The majority of the power supplies for the ISR were manufactured and designed by industry to performance specifications in 1968/70. At that time it was difficult to obtain components to the required performance e.g. reference sources, operational amplifiers, current transducers, etc. Also complicated power circuits were used to overcome the non availability of high voltage grade thyristors. Nowadays, none of these items limits the performance of power supplies the only remaining problem being to obtain manufacturing quality to the standards demanded by the present specifications for reliable operation. Initially modifications were made so that the power supplies performed to their original specifications over long periods of time. It became apparent with the evolution of the ISR well beyond its original design that improved performance of the power supplies was required to give adequate low background counts for the physics experiments.

Original Specifications

Power Supply	Current Stability $\Delta I/I$	Ripple		Equivalent Current ripple at 50 Hz
		$\Delta U/U$	$\Delta I/I$	
Main rings	3.10^{-5}	1.10^{-4}		5.10^{-8}
Pole face windings	1.10^{-3}		5.10^{-6}	5.10^{-6}
correction windings	2.10^{-3}	1.10^{-4}		3.10^{-7}

The original stability and ripple figures were derived from the requirement of stability of the closed orbit and Q variation of the beams. Ripple was considered as the residual after rectification due to transformer unbalance, firing circuits etc. and consisted of 50 Hz and above. Small current perturbations (ΔI) of the order 10^{-6} to 10^{-7} cannot be directly measured but are derived from the power supply output voltage fluctuation (ΔU), the angular frequency of the fluctuation (w) and the magnet time constant (τ):

$$\frac{\Delta I}{I} = \frac{\Delta U}{wL} \cdot \frac{R}{U} = \frac{\Delta U}{Uw\tau}$$

Effects of power supplies on the beams

Machine development tests had deduced that changes in Q of 10^{-6}, equivalent to a current change of 10^{-5} on a power supply could be detected on the loss rate[2]. However, it soon became apparent that fluctuations in the output current of power supplies well within the original specifications had large effects on the background at the physics experiments.

Frequency tests. A constant voltage variable frequency signal was generated on the output of a power supply at the end of a physics run with the following results.

Freqency Hz	Effect on background count (log scale)
50 and above	no measurable effect
10	x 2 increase in jitter
1	x 25 increase in jitter

Step tests. A test programme which adds and substracts 1 bit every 1 s to the DAC of each power supply in turn whilst monitoring the effect on the physics background tests the response of the beam to every power supply in the ISR. Any anomalies from test to test can reveal: poorly adjusted power supplies, magnets in sensitive positions, wrongly specified power supplies, badly set-up beams, etc. During this step change, to any power supply which affects the tune of the machine, a very large perturbation is observed, but under steady state conditions changes of up to 0.2% have little effect on background. Therefore, the change should be considered as a ripple effect. The majority of DAC's are 12 bit i.e. 1 bit step represents 244 ppm of max. current. The current loop of a power supply has a time constant of 0.05 s (3 Hz bandwidth). Therefore a 1 bit step gives a maximum rate of change of current of:

$$\frac{1}{I\max} \cdot \frac{\Delta I}{\Delta t} = \frac{244.10^{-6}}{0.05} = 5.10^{-3}s^{-1}$$

The ripple specification for the pole face winding power supplies is 5.10^{-6} at 50 Hz which corresponds to a maximum rate of change of current of :

$$\frac{1}{I\max} \cdot \frac{\Delta I}{\Delta t} = \frac{5.10^{-6}. \Pi}{20.10^{-3}.2} = 4.10^{-4}s^{-1}$$

From these results it can be seen that if the original ripple specifications had been extended down to frequencies below 1 Hz then adequate performance would have been obtained.

Fluctuating power supplies. Examples of power supplies fluctuating within specifications giving unacceptable physics background counts have been experienced e.g. a tuning quadrupole power supply with a fault fluctuated by 10^{-3} causing unacceptable physics background counts. This fluctuation was of a random step nature and if considered as ripple it would have been outside the specification. Another example was the main ring power supply current loop having an inadequate phase margin which produced 3 Hz damped oscillation on the output. The amplitude of this was 20 mV which corresponds to a current ripple at 3 Hz of:

$$\frac{\Delta I}{I} = \frac{\Delta U}{Uw\tau} = \frac{20 \ . \ 10^{-3}}{1700 \ . \ 2\Pi \ . \ 3 \ . \ 7} = 10^{-7}$$

This ringing could be seen on the physics background and was eliminated by improving the phase margin of the current loops.

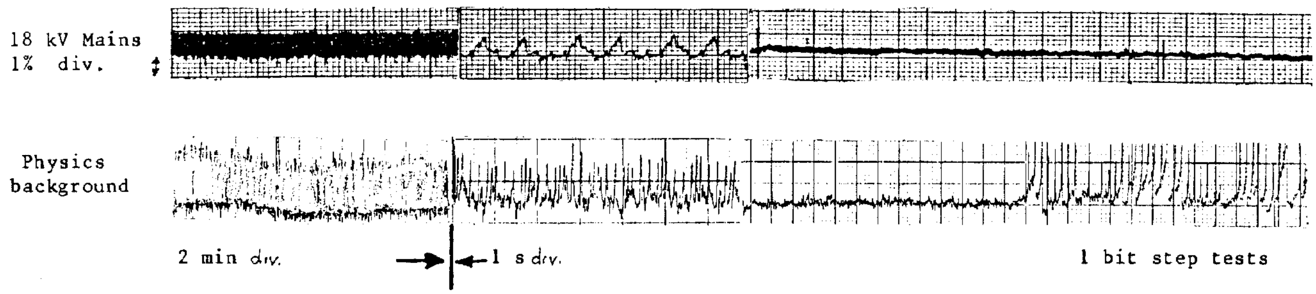
To enable fluctuations to be detected, the output of each power supply is equipped with an independent, ultra sensitive, voltage spike detector which signals all changes to the control computer.

Sources of power supply perturbations

The LF noise on the output of a power supply comes from two sources: 1) internally generated noise from amplifiers, reference sources, pick-up from external sources and 2) external sources, i.e. the mains supply.

With the addition of the CERN Booster, pulsed switching magnets and the pulsing of beam lines for energy conservation all of which are synchronised to the PS cycle with a repetition rate around 2 s the LF noise on the CERN Lab. 1 mains is considerable[3].

This noise appears directly on the output voltage of the power supplies reduced by the rejection of the control loops around this frequency. Also it appears on all A.C. feed lines to other apparatus e.g. electronics, DCCT etc.



Improvements to reduce internally generated noise

These modifications include items such as: better screening, avoidance of earth loops, improved firing circuits to reduce subharmonics, better reference sources, etc.

Reference source. The output of a power supply can only be as good as its reference source. One of the major improvements to all of the ISR power supplies was obtained by mounting in each power supply its own computer controlled voltage reference source: 16 bit DAC[4] where the highest performance is required and 12 bit DAC (the 12 least significant bits of the 16 bit DAC) for the remainder. These DAC's have low noise, true 16 or 12 bit performance and 10 V maximum output whereas commercial DACs still do not offer adequate performance. These DACs improved the LF noise on the output of the main power supplies from 10^{-6} to 10^{-7} and the corresponding improvement of 10 times was obtained on all other power supplies.

Control loops. Some of the improvements here were associated with reliability and were already described under component improvements. Another example was curing the oscillation coupled through the mains of the ISR main power supplies (2 x 6.9 MW) by increasing the margins in the cross over of the voltage control loops. The use of voltage comparison instead of current summing between the DAC and DCCT signals eliminates the need for precision resistors, the only remaining precision resistor being the current to voltage conversion in the DCCT.

Remote control. A new CAMAC orientated remote control system which can measure the output current of a power supply to an absolute accuracy of ± 10 ppm of max. value has been installed which enables the performance of the power supplies to be checked out more precisely. Coupled with this a standards lab has evolved where the volt and ampère can be referred to National Standards to an absolute accuracy of ± 5 ppm and ± 10 ppm respectively. Thus it is possible to calibrate power supplies to an absolute accuracy of ± 30 ppm and verify their long term stability.

Improvements to reduce mains born noise

The rejection of the control loops to mains born noise around a frequency of 1 Hz was increased as far as practical with the existing hardware, yet effects on the background due to pulsed loads on the mains could still be observed.

Measurement of mains born noise. Conventional measurement of mains perturbations does not give a good correlation with effects on the beam. However, by sampling for 1 ms on the peak of the 50 Hz sinusoid good correlation between noise on the mains and the physics background count is obtained. This type of measurement also gives a response to any harmonics which may be present on the wave form. From recordings over a period of time it was clear that the major source of mains born noise is generated within CERN.

Stabilisation of mains supply. For small important AC loads e.g. DCCT, a mains stabiliser is used to reduce the effect of the mains noise.

Isolation of ISR power supplies from noise producers. CERN Lab. 1 is supplied at 130 KV and stepped down to 18 KV by 3 x 30 MVA transformers. The short circuit capacity at the 130 KV level is 2500 MVA and at the 18 KV level 540 MVA. By supplying the ISR from 1 x 30 MVA and the rest of CERN from 2 x 30 MVA the point of common coupling to the other CERN noise producers was moved up from the 540 MVA level to the 2500 MVA, level giving a 5 times reduction on the noise seen by the ISR from the rest of CERN. To limit the harmonics produced by the power supplies a 7.5 MVAr capacitor bank was connected on the ISR side; the rest of CERN having its own harmonic filter. The improvements to the mains noise is seen directly on the physics background counts and all other ISR users benefit from this reduced noise level.

Conclusions

The reliability of the ISR power supplies has been improved up to the high standard where it is rare for a beam to be lost due to a power supply failure and all systematic faults have been eliminated. This has been achieved with the minimum replacement of original equipment. The performance of the ISR has evolved considerably above its original design aims such that currents of up to 40 A in each ring remain after acceleration from 26 to 31 GeV/c. Under these conditions the beam occupies most of the available aperture which makes severe demands on the performance of the power supplies. The power supplies have been improved up to the limit achievable with the present hardware and they surpass their original performances by at least an order of magnitude. One of the most important factors for good physics conditions is minimum power supply noise in the frequency range 0.1 to 10 Hz. In this region the noise has been reduced 100 times and is now in the range 10^{-7}. The original ripple specifications now apply as low as 1 Hz.

Acknowledgements

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