HIGH STABILITY HIGH CURRENT PROGRAMMED POWER SUPPLIES FOR NIMROD EXTRACTION SYSTEMS

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Introduction

Proton beam extraction in the Nimrod P.S. is at present by energy loss target, a radially focusing quadrupole and extraction magnet. The existing magnets are 'C' core but the use of sextupole magnets in the near future dictates the use of very high current systems. The proposed extraction by Q'2/3 resonant node requires even higher current levels.

This paper describes briefly the high stability step programmed power supply for the double extraction system now in successful operation and the new high current 21,000A pulsed power supply for septum magnets for the future extraction system.

The step programmed power supply was developed to increase machine utilization by switching the proton beam between two beam lines in the same machine burst on flat top. The supply can switch a maximum of 500A up or down in 10ms and maintain a dc level stability of ± 0.002%

The maximum current capability is 1650A with current levels fully variable to cover the energy range 7.5 GeV. Preliminary data was first published at the Second International Conference on Magnet Technology held in Oxford, England, in 1967. Since then many modifications have been carried out dictated by changing load requirements and operational experience with the system. The first part of the paper reviews the system techniques and results obtained.

The second part of the paper deals with the pulsed power supply now under design and construction using a homopolar generator; the load current being programmed by a series transistor regulator. A very brief review of other possible systems which were considered is included to show reasons for the choice. The design specification requires that the current waveform should be trapezoidal and rise linearly in 200ns to 21,000A max. Stability during flat top time should be within 0.2% inclusive of ripple. The flat top time is of the order of 600ms thence the current decreases linearly to zero in a further 200ms. The maximum FRR is 25 pulses/min.

Part I Step programmed system for double extraction

Basic Principles. Fig.1 shows the simple block diagram of the system.

(i) Current stabilization is via the series regulator.
(ii) Switch on control by opening the power loop via SCR 1 and 2 and allowing the magnet current to decay to the required level via flywheel resistor R.
(iii) Switch on control by applying a forcing voltage from energy store to introduced into the loop via diode D.

Both switching modes rely on a strobe amplifier detector to achieve in (ii) reclosing of the loop and in (iii) switching off the forcing supply. The pulses produced by the strobe also control the logic sense for various other operations in the system.

The supply is built round a compound dc generator (rated at 1650A 110V) voltage stabilized and forming the main supply. It is better on a supply of this nature to use rotating machines rather than static rectifiers since (a) the mains system is buffered from fast power changes which are ironed out by the rotor rectifiers, (b) the much smoother output from the M/G permits working without static filters or the complications of dynamic ones. Static filters of the choke input type could not be used if speed is to be achieved at low cost. The very low armature inductance adds very little to the system's stored energy which is virtually all in the magnet load.

The M/G set is voltage stabilized in a conventional manner the fields being finally fed and controlled by an amplitune. It was not considered necessary to aim for a highly stabilized voltage and the dc voltage stability of ± 0.1% achieved was considered more than adequate.

Current stabilization loop. This is somewhat conventional in its dc mode. It has a precision voltage reference source which can be switched to the two variable levels and correct monitor feedback via three shunts (500; 1000; 1500) all of 17 F.D. Each shunt covers a given range of beam energies and enables the signal/noise ratio of the monitor signal to remain fairly constant from the maximum current down to about 200A. The shunts are connected into circuit via a link board. To achieve a monitor stability equating to that of the reference source the shunts are temperature controlled about the peak flat of the temperature resistance coefficient curve. A temperature stability of ±0.2°C has been achieved corresponding to changes of about 5 parts/million.

The regulator is a three stage "Darlington" configuration of some 432 pnp transistors (2N1100) in 24 discreet blocks each with driver and pre-driver stages. Each transistor has a 0.5A resistor and a 6A fuse in the emitter. The bases are diode blocked and balanced into the driver. The emitter fuse protects the system against faulty transistors, acts as an automatic counting device, and indicates the defective transistor. The pre-drivers are fed from a power boosted error signal amplifier via fanned out balancing circuits. This amplifier is preceded by a comparator amplifier which sums the reference and current monitor voltages. The error amplifier normally has a forward gain of 11000 but during switch down its reversed output is clamped and it is converted into a divider (factor 47). The divider mode is allowed to persist beyond the current catch point by a delay on the line closure pulse. This gives good control of the catch point. The original system used two loops, one being an AC coupled...
Voltage feedback from the magnet bus with a cross over frequency of 2.5 Hz. The AC loop has now been removed and the overall bandwidth of the current feedback considerably increased. This has simplified switched control problems.

Regulator protection The regulator is protected against excessive temperature rises; collector dissipation exceeding the safe ratings; and over voltage. A crowbar consisting of SCRs backed up by an air operated shorting switch is used for the two latter conditions and the base input to the drivers has a zener clamp (clamp voltage 40V).

Load faults (where the magnet may have shorted turns or worse) will drive the transistors from the safe working area into breakdown regions. The voltage and current load i.e. Vcc and Ic are in consequence continually monitored.

These two parameters are converted into log functions and summed by an amplifier the output of which must produce a voltage proportional to Vcc. No scaling of this is taken. This voltage is instead set against a reference the final summation voltage driving a Schmitt trigger circuit.

This will produce a pulse out to the crowbar gate if Vcc rises higher than the preset trip reference.

Overvoltage Normally the zener clamps take care of possible overvoltage conditions. If, however, for any reason the regulator voltage exceeds this value (40V) by 2% the crowbar circuit is triggered by an extension of the load fault detector.

Failure Each emitter is fused by a type FU 60C fuse. These fuses have small spring leaves which open on failure, the rear leaf is used to connect the crowbar circuit whilst the front leaf gives visual indication. The crowbar circuit can be preset to trip between 2-40 transistors failed.

Stopping Programme The heart of this is the strobe unit. This is an amplifier (Motorola MC64433) operating open loop with the inputs fed by the reference and current monitor voltages using zero crossing technique. The inputs have pulse driven clamps and the system under dc conditions will have either one or other inputs clamped. This is to prevent pulses being produced by the current monitor voltage crossing the reference voltage under servo conditions. When both input channels are unclamped crossing of the current or reference volts will produce a change of output from one level to the opposite polarity.

Differentiating can produce pulses to control the system functions. All system pulses are arranged to be 10V 10µs 100A source.

Switching Referring to Fig.1 and assume there is current in the loop, if the system accepts a current down command pulse this after delay will be fed into SCR2 gate which commutates out the line SCRs (the commutation is modified class E). The current in the regulator loop falls to zero and the reference is changed over to the new level. The same pulse reduces the loop gain via the error amplifier and increases loop bandwidth.
The magnet current will now decay exponentially via the flywheel resistor R. The strobe amplifier meanwhile examines the reference and current levels and when cross over occurs produces a pulse to trigger the line SCR,1. The regulator now retakes control of the current to stabilize at the new reference. The same line closure pulse will restore the loop gain after delay and clamp the strobe current monitor input. During switching the regulator is out of loop and no voltage appears across it. The line SCRs blocking the P.E.M.P, etc.

Switching up. The reference is now switched back to its original level and the regulator will be driven into forward saturation. However to switch up at the same dI/dt as decay, a voltage component equal to dI/dt must be provided. Energy and volts are ensured by a bank of capacitors (C) 0.07F charged to 450V (variable).

After reference change over a pulse is fed to the pump SCRs,4 and the line diodes (D) will be reverse biased.

An inductor in the capacitor bank bus and shunt capacitors across the diodes ensure that the current in the diodes falls to zero and the dI/dt reverse bias is within the device capabilities. Without this protection the diodes (D) would punch through. This also applies to the flywheel diodes which are included to block any current passing back. The only current path therefore is through the magnet. The capacitor bank is now in series with the generator, the magnet 'sees' Vb + Vc and the current can be made to rise at approximately the same speed as decay.

The strobe again examines the reference and current levels and produces a pulse when cross over occurs. This is used to trigger commutating SCR,3 the forcing volts are turned off and the regulator retakes control to stabilize to the reference level.

A small pre-determining voltage of adjustable level and polarity is switched into the strobe enabling the control pulse to be produced before or after cross over to offset system delays or other abnormalities.

General. Initial trouble was experienced with the load. The magnet is in a stainless steel can which was pumped to partial pressure and when stepping with the higher voltages needed we experienced 'Paschen' breakdown phenomena. This caused serious damage and the magnet is now run at atmospheric pressure.

The design was originally arranged for switching from the higher to the lower current level and back again in the same machine flat top. This allowed for two fast spills at start and end of flat top and a long counter type spill during flat top.

Since the existing magnets are solid core it was known that difficulties due to eddy currents would arise and a series of laminated magnets are being made. At the present time, however, in order to use the system and to minimize the eddy current effects on the gap flux distribution, the operation has been reversed and only one fast spill is available. The step is fast and short from the lower level to the upper and down again the excursion to the upper level being maintained for < 200ms.

However, the phase shift between the mean flux and the current has caused some serve problems since fed back voltages back or boost the main supply producing errors beyond the servo control capability. This has been overcome by pre determination of the strobe catch point but we loose 10ms of stable current time after switching.

Laminated magnets should overcome this problem however, and the first will be ready for test in March 1969.

The relief resistor in the collector of the regulator bank was included after a magnet change when it was found the new magnets' resistance was nearly 20% higher than the specification. This necessitated higher voltage working and the resistor absorbs the additional voltage at the lower current level when maximum volts appear across the regulator. Automatic insertion is assured since the regulator current passes to zero when switching down thus opening the shunt SCRs. These are gated by the forcing supply (SCR,1) 'ON' pulse at switch up.

This particular method of current level switching with inductive loads offers wide scope since it is limited only by (a) the load winding and terminal insulation and (b) the SCR,1 IED and PFG limits. The delicate transistor system is 'volt free' when switching takes place. Since SCR,1 can be series connected very high voltages could be accepted.

The line SCRs,1 on our system are four GE type 0220P cells in parallel while the relief resistor about in four type 0220B. Anode inductors are fitted to limit the dI/dt at switch on to 50A/µs and also serve to balance the current sharing. By fitting two reed relays in each inductor thus utilizing its field and connecting in 'and' or 'or' and mixing, we can protect against gating errors should one or more SCRs fail to gate.

Tests have been carried out above the designed limits and we have switched up to nearly 1800A from 1150A. To date the system has worked very reliably to specification and the long term stability has been extremely good.

Part II Septum extract magnet power supply

The original specification called for a maximum magnet current of 20,300A and the power supply was fixed therefore at 21,000A. The system is designed for a power loop having a resistance of 1.5mΩ and inductance of 56mH although these could well be less. For thermal and economic reasons pulsed duty is used as explained. In the introduction the dI/dt rise and fall being fixed at 10A/µsec.

Taking our normal running time the saving/annum in power by pulsed operation is about half the capital cost of the supply. If we have to operate the capital cost of the system is considerably increased. A power unit of 1MW against 600kW would be needed and cooling plant requirements would be up by nearly 20%. The moral is obvious - pulse where you may!
Since the magnet inductance is very low, ripple voltages must be suppressed. At the same time the system must be programmable. This tends to rule out static filters whilst dynamic filters produce other problems. It is far better for the supply to be inherently ripple-free. As Confucious might have said 'where there is no ripple the problem of elimination does not arise'. Hence the homopolar generator.

**System design:** The unit is designed around the homopolar generator (H/G) with a series transistor regulator for programming. It is not possible to drive via the H/G fields since the long time constants do not permit fast functions. It can be shown that field power \( P \propto \frac{1}{\nu} \) the field power limit dictating response. The only valid consideration therefore is to fix the machine bus volts and programme by other means, a series regulator being the only practical approach at present.

Before the decision to use the above system was taken, consideration was given to other methods: (a) Multiphase SCR control; (b) Multiphase rectifiers; (c) Batteries; (d) Conventional commutator machines; (b), (c) and (d) require series regulators.

With SCR systems we have a yardstick with the 16000A 60V unit at CEZN-11a. Gate jitter can enhance ripple and render use of dynamic filters essential. (One can use an SCR system with static filters and series regulator).

The space requirement for housing the supply is large and the capital cost is high. The same comments virtually apply to (b). Both systems are liable to cause harmonic distortion of the mains and pulsating load conditions, unless counteracted by saturable reactor systems, will cause mains fluctuations.

Batteries (although the system seems odd) are quite valid. They would, however, need a trickle charger (12000A!) and maintenance together with gas dispersion problems and difficulty of switching out for full clearances effectively rules out their use. Space is also a problem.

Conventional commutator machines are near design limit unless one uses multiple commutators. High cost coupled with maintenance and copper dust production do not make them attractive. Ripple with an extremely wide spectrum still has to be eliminated.

A homopolar generator with series regulator can offer more than all of the other systems. Complete isolation from the mains is achieved whilst the rotor inertia buffers against violent mains disturbances. Ripple is almost non-existent. The H/G is very simple extremely robust and maintenance will be very small. A further attractive feature is space, the machine requiring a floor area of only 12ft. x 4ft. If we add the regulator 10ft. x 3ft. and 6ft. x 2ft. for control racks these complete the total system space requirement.

**Generator** The H/G will be a two stage drum type rated at 600kW 15000A 40V de 5% regulation at 21000A, being designed and built by International Research and Development Co. Ltd., Newcastle, England. It is designed to have the new 'wearless' brush developed by that Company and research is proceeding with the design of this
current collection system. Maintenance should be minimal.

No attempt will be made to stabilize the H/G voltage due to field time constants. The field current is stabilized instead and the amplitude control is made to the maximum reference and function voltage levels. The field is intended to be fed from the generator bus via a small series regulator.

Ripple The H/G is designed to produce an output voltage with ripple content of 0.01% of peak volts. Apart from brush noise (which is easily filtered out) the basic frequencies will be a function of rotation. The generated ripple will therefore be approximately 50Hz and its multiples. The estimated 50Hz pk/pk ripple current in the magnet at 20000A is approximately 0.25A or 0.00125%, the higher frequencies being correspondingly smaller.

Reference System The reference is made up of two voltages, viz: A precision dc voltage and a trapezoidal voltage function the amplitude of which is always arranged to be greater than the dc source. Both of these signals are fed into a strobe amplifier unit (again a zero crossing device) and pulses are generated at times of the functions' leading and trailing edges on the dc source. These pulses are used to switch the two sources at the comparator amplifier input and the current will therefore follow the function leading edge until crossover thence the dc precision reference during flat top and fall with the function trailing edge. This system has been developed since it is easy to produce a trapezoidal function but not with a precision flat top stable and repeatable to 0.002%. Fre-quency voltages will be fed into the strobe to enable the crossover to be predicted to counteract system delays.

Current control The load current is controlled via a series transistor regulator the H/G being constantly excited. The regulator is a 3 stage system using some 2800 transistors in the main stage. The transistors chosen are gain selected R.C.A. 2N3772 each having a 0.2A emitter balancing resistor and fuse.

A % failure counter is incorporated using the emitter fuse (see Part I). Care has been taken to ensure that no distribution using the regulator is as even as possible and that all case temperatures are approximately the same.

The first driver uses RCA type TA2669 (a fast 6CMHz overlay device) and the overall bandwidth should be approximately 20kHz. Sensing the collector power P2 is the same as described in Part I. The current servo starts off with a conventional reference and monitor voltage comparator and error signal amplification with a power output stage. A feed forward drive is added and circuit output is added and circuit exit and entry is controlled by the strobe. The two drive currents derived from the feed forward and servo error loop are mixed at the regulator first drive stage base input via blocking diodes. The feed forward drive (programmed with a penthouse function) can be adjusted to compensate for transient drive requirements etc. The closed loop can therefore be arranged to provide the dc error signal drive component locked with the amplitude requirement only. At the beginning of flat top the strobe pulse clamps the feed forward drive and overshoot can thus be eliminated giving a precise turnover. The same pulse can be used to increase the loop gain and introduce any compensating networks achieving precision control.

Protection No breakers are included in the power loop. Clearance of the bus voltages are proposed by connecting the SCRs than disconnecting the field from the bus and allowing the system to go into current resonance with a capacitor bank. Since this circuit is diode blocked the current will zero after √2 the decay being of cosine form. Calculations show the bus clearance will be approximately 0.10s allowing 2kV rise across terminals. Remnant voltage of the machine is stated by the manufacturer as 0.3V.

In case of major faults a fuse is included since the prospective fault current and power is 3 x 10^3A and 12MW respectively. The fuse has an apparent rating of 20000A.

di/dt detection Uncontrolled rates of rise can be detected and countered (possibly before the current reaches large amplitudes) by using the inter bus field and a search coil. The voltage output will be a function of di/dt and if calibrated to drive a Schmitt circuit a trip pulse can be produced if the di/dt exceeds the normal even by very small amounts. Conventional over current protection is also included.

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References

4. Determining max. reliable load lines for power transistors, Motorola Semiconductor Tech. Inf. (AN 137-R1).