

## **CONTROL STRATEGY FOR THE MAIN MAGNET POWER SUPPLIES OF THE K-500 SUPERCONDUCTING CYCLOTRON**

Biswajit Sarkar, Anirban De, S. K. Thakur, C. D. Datta, Debranjana Sarkar, Subimal Saha  
*Variable Energy Cyclotron Centre, 1/AF Bidhannagar, Kolkata – 700 064, India*

### **ABSTRACT**

The main magnet of the upcoming superconducting cyclotron at this Centre consists of two superconducting coils. Two current-controlled power supplies are used to energize the magnet coils. In order to ensure proper, convenient and safe operation of the main magnet power supplies, an appropriate control strategy has been designed around them. The control strategy encompasses both the protection as well as the supervisory aspects. The protection strategy is responsible for the safety of the power supplies, the magnet coils and the operating personnel from potentially hazardous eventualities. Since it is not practicable to operate these power supplies from their local panels, supervisory software with an easy-to-use Man-Machine Interface (MMI) has been developed so that the power supplies may be operated and monitored from a remotely located control console. This paper provides a brief overview of the scheme that we have developed.

### **INTRODUCTION**

A superconducting cyclotron (K-500) is under construction at this Centre [1]. Two superconducting coils – named ‘Alpha’ and ‘Beta’ – would create the main magnetic field of this cyclotron. The cable used for the magnet coil is Nb-Ti wire with 500 filaments, each of which is 40  $\mu\text{m}$  in diameter. The wire is embedded in copper channel for cryogenic stability. The coils are kept immersed in liquid-He at 4.2 K inside a specially built stainless steel cryostat. The cryostat, housing the superconducting coil, the liquid-N<sub>2</sub> thermal shield and the outer vacuum chamber is placed inside an iron core magnet for generating magnetic field of up to 5.5 Tesla.

Depending upon the nature of the particle to be accelerated, these two coils (along with several trim coils) would be energized to different levels to obtain the desired isochronous field pattern. Two dc current regulated 20 V, 1000 A power supplies are used to energize the main magnet coils. The power supplies consist of two windings (in star and delta configuration) on the secondary of the transformer. This is followed by 12-pulse thyristor-based controlled rectification scheme. The outputs from the rectifiers are connected in parallel using an inter-phase transformer (IPT). During normal operation, the IPT absorbs the voltage difference between the star and delta windings to ensure proper current sharing amongst the secondary windings. High-current water-cooled transistor banks are used as the series-pass element for current regulation. The output current stability of the power supplies is within 10 ppm, including long-term drift, line and load regulation and output current ripple. The power supplies employ 18-bit digital-to-analog converter (DAC) and 16-bit analog-to-digital converter (ADC) to effect the current setting and readback respectively. To achieve precise current setting, the DAC is housed in a temperature-controlled oven for minimizing temperature-induced drifts. The power supplies are also equipped with RF shielding and filters as a safeguard against conducted and radiated noise in the cyclotron environment.

A set of interlocks is provided to shutdown the power supplies automatically when operating situations so demand by disconnecting them from the three-phase power source. The interlocks function as a safety feature and are used to protect the power supplies, the magnet coil and the operating personnel from potentially unsafe conditions. The interlocks may be designated as either internal or external. The internal interlocks shut down the power supplies for eventualities like phase failure, cooling water flow failure, over temperature of the power supply components, transistor failure or over current. The external interlocks, as the name itself indicates, ensure that the power supply is put off when conditions external to the power supply (viz. magnet coil) are unfavourable.

The power supplies feed to a set of highly inductive coils (Alpha coil ~13 H, Beta coil ~27 H). During normal operation, the coils have an enormous amount of energy stored in them (~22 MJ maximum). Thus, when the power supplies have to be put off, this stored energy must be dissipated

external to the cryostat. Two resistors – named ‘slow dump resistor’ and ‘fast dump resistor’ – are connected across each coil to dissipate the stored energy in the coils slowly or quickly, as necessary. The slow dump or the fast dump action is controlled by the opening or closing of two contacts – the series contact and the shunt contact. Fig. 1 shows how the coils, the contacts and the dump resistors are connected across the power supplies.

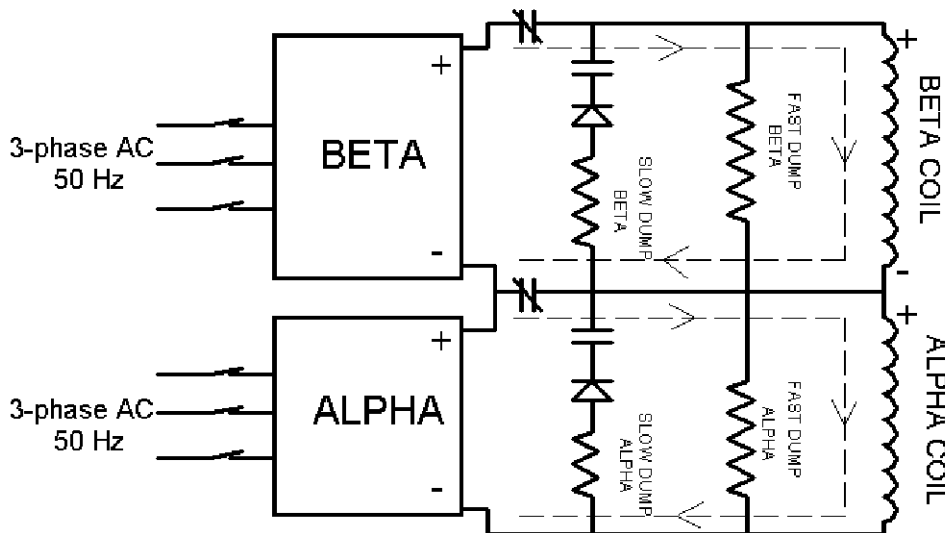


Fig. 1. Schematic diagram of the main magnet power supplies connected with superconducting magnet load and the dump resistors.

Each power supply is equipped with an intelligent controller that is able to set a given current value on the DAC, read ADC output and sense various interlock status. It is also able to communicate with a remote computer over a serial link (RS-232/422) using a set of ASCII strings, following a command-response protocol. Thus, the power supplies may be operated and monitored from a remotely located control console.

During beam-tuning operation of the cyclotron it is necessary to manipulate the current flow through the magnet coils to alter the field profile in the desired manner. It is therefore imperative that an easy-to-use MMI is provided to the operators so that they can supervise the power supplies from the control room. With this end in view, supervisory software has been developed for remote setting and monitoring of the power supplies. Related MMI developments have also been reported elsewhere [2].

## THE CONTROL SCHEME

During normal operation of the power supplies, the series contact remains closed and the shunt contact remains open (see Fig. 1). In this condition, the slow dump resistor does not remain connected across the coil. Only the fast dump resistor remains connected. However, since the resistance values of the fast dump resistors are much higher ( $R_{F(\text{Alpha})} = 167 \text{ m}\Omega$  ;  $R_{F(\text{Beta})} = 250 \text{ m}\Omega$ ) than those of the superconducting coil, no current flows through them.

During operation of the power supplies, if any operating condition deviates from what is specified, the power supplies are automatically shut down. For example, if the cooling water flow reduces or stops, the power supply will be tripped under the action of the appropriate interlock. This will ensure that no power supply component gets overheated. However, mere shutting down the power supply will not suffice; it will also be necessary to dissipate the energy stored in the coils. This is done by closing the shunt contacts immediately. This will ensure that the slow dump resistors are introduced in parallel to the coils (see Fig. 2). Under this condition, even though the fast dump resistors remain connected, the current decays mainly through the slow dump resistor because of its lower value ( $R_{S(\text{Alpha})} = 5 \text{ m}\Omega$  ;  $R_{S(\text{Beta})} = 7 \text{ m}\Omega$ ) compared to the fast dump resistors. Fig. 3 shows how the currents decay with time during slow dump. It should be realized that slow

dumping is done when the operating conditions deviate from the specified values, but the deviated condition is not potentially catastrophic and it is acceptable to dump the energy relatively slowly.

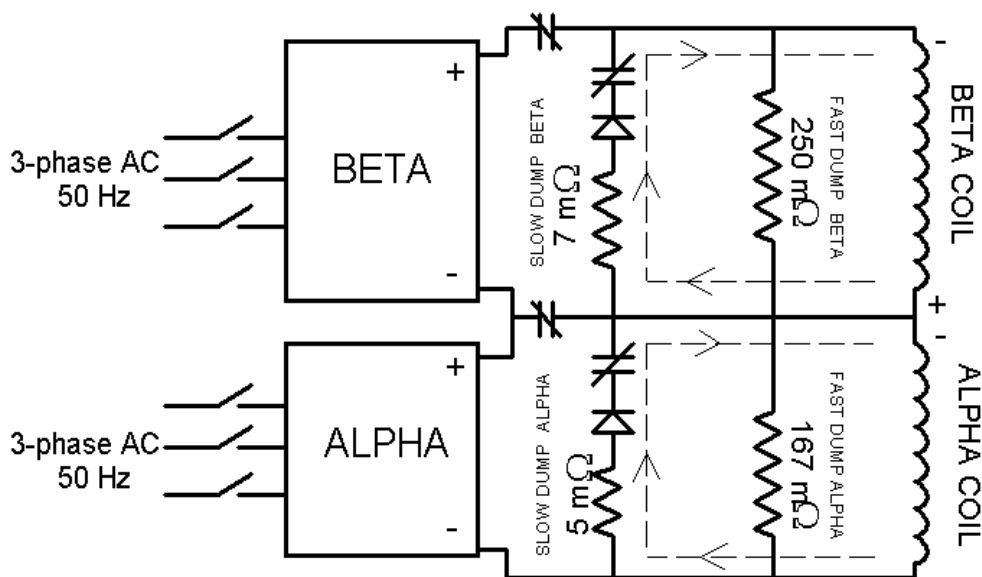


Fig. 2. The states of the two contacts when slow dump is in progress

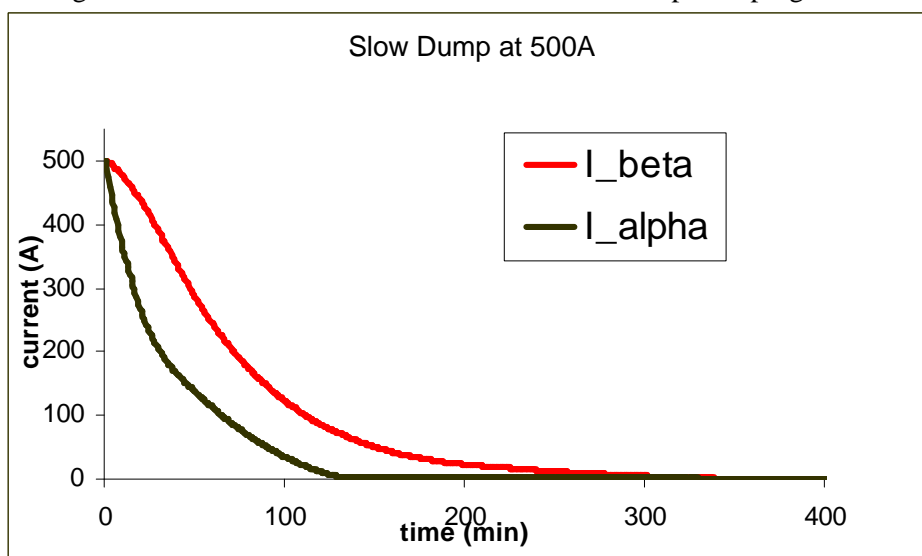


Fig. 3. Profile of current decay for slow dump initiated at 500 A

In the eventuality that the operating condition has deviated drastically from the normal operating condition, thus giving rise to a potentially catastrophic situation, it becomes imperative to dump the stored energy quickly. This is the case, for example, when there is a sudden loss of a substantial amount of liquid-He from the cryostat. In this situation, both the series and the shunt contacts are opened so that only the fast dump resistor remains connected across the coil (see Fig. 4). Since  $R_F > R_S$ , the currents decay rather quickly. Fig. 5 shows how the currents decay with time during fast dump.

There are several operating conditions, deviation from each of which warrants the initiation of a fast dump or a slow dump action. All the set of conditions demanding a given action are logically OR-ed and appropriately connected to the corresponding relay/relays. All circuits have been so designed as to ensure fail-safe operation of the system.

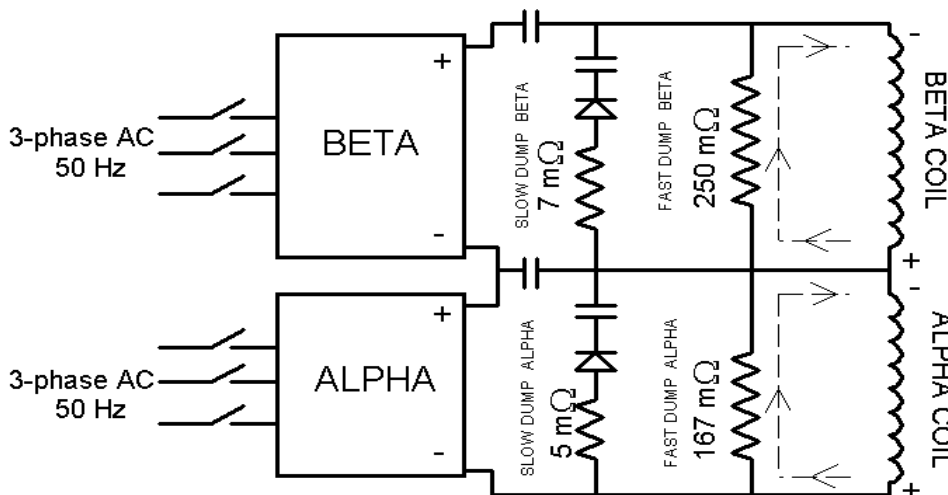


Fig. 4. The states of the two contacts when fast dump is in progress

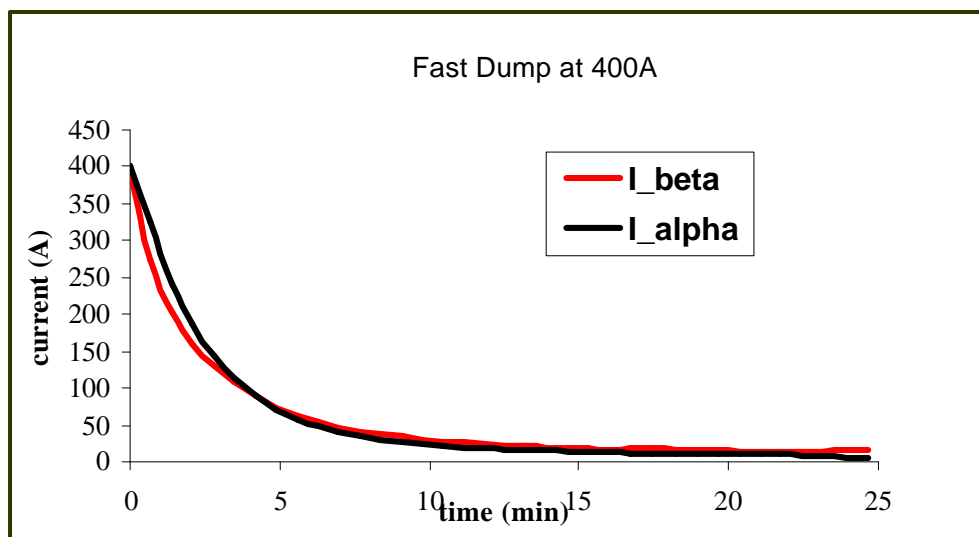


Fig. 5. Profile of current decay for fast dump initiated at 400 A

It has already been noted earlier that the power supplies are equipped with intelligent controllers and serial interface through which it is possible to supervise them from a remote location. In order to implement the supervisory scheme, we have connected the two power supplies to each of the two serial ports (COM ports) of a host device on the Local Area Network (LAN) in a point-to-point fashion. Even though a multidrop topology is preferable to a point-to-point topology from cabling point of view, we have deliberately preferred the latter option to reduce the overhead of selecting a power supply (by addressing it) before a command for that power supply could be dispatched. For communication between the host and a power supply, we have chosen the RS-422 standard in preference to RS-232.

The software, having a comprehensive and easy-to-use front-end, has been developed using Microsoft Visual Basic 6.0 on a personal computer running Windows 2000 operating system (see Fig. 6). The front-end allows the operator to interactively specify the desired time profile of the current change for each of the coils. As many as sixteen such profiles may be defined and stored at a time, and a particular profile may contain as many as sixteen steps. A specific profile may then be used to trigger a power supply. So long as a profile is running, the current will change in the corresponding coil following that profile and hold on to the final value. It is also possible to

asynchronously halt the run of a profile, to continue the run that has been halted or to stop it altogether. The front end also displays the actual current delivered by each of the power supplies, and the instantaneous deviation of the actual current from the corresponding set value. Moreover, it provides the status of the profile with which a power supply is triggered. It shows if a profile is running (or halted or stopped) and the step at which it is running (or halted). Over and above the profile-based setting, there is also a provision for fine-tuning the current setting. For this purpose three *spinners* are provided using which the current setting can be altered in three modes viz., coarse, medium and fine. Provision also exists for an on-line display of the status of the desired interlocks.

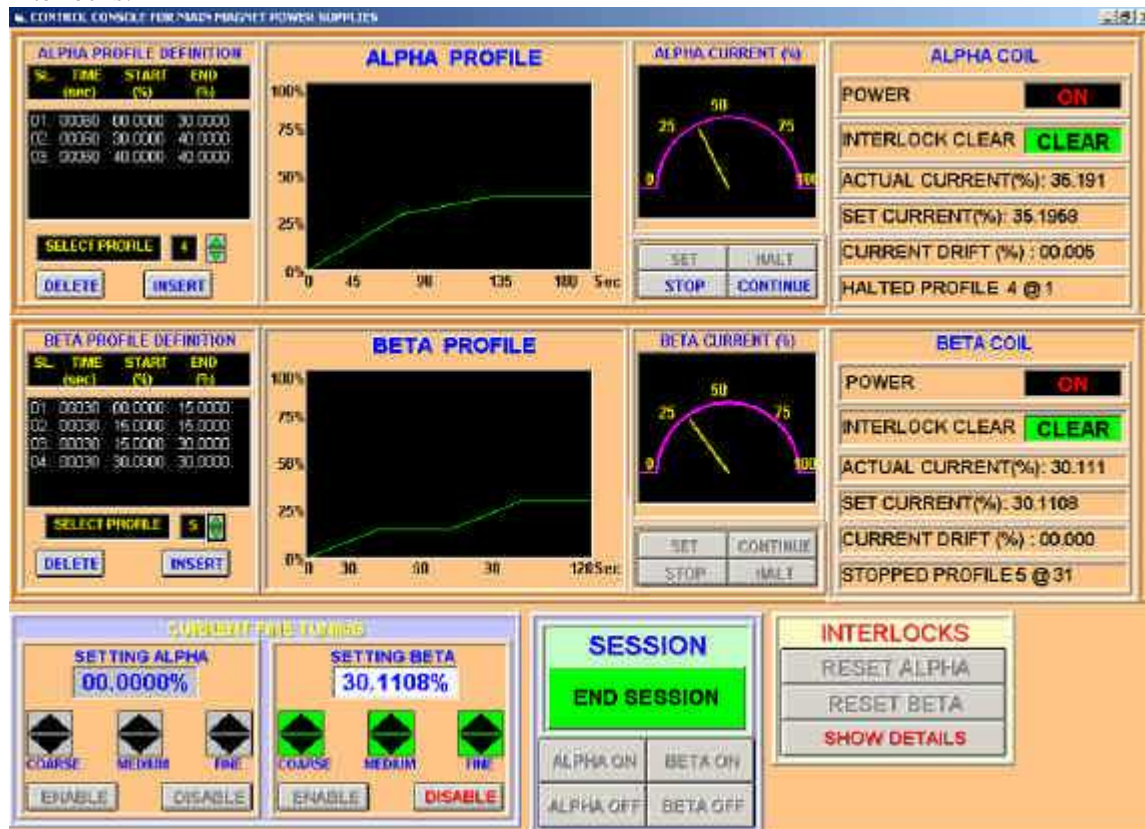


Fig. 6. Man-Machine Interface of the supervisory software for operation of the main magnet power supplies

In addition to operating the power supplies, it is often desirable to have a continuous log of the values of the various parameters of the power supplies with time. This would not only help identify the parameters causing a possible trip (along with the exact time of occurrence of the trip), but also carry on an offline analysis of the data to identify an optimum operating range of the system parameters. The software uses an Oracle 9i database server at the back end. The values of the various power supply parameters (like set current, actual current, interlock status etc.) captured during each monitoring cycle are inserted into the database. All communication between the database server and the client machine takes place over 100 Base-T Ethernet LAN running TCP/IP protocol. Database access for insertion, updation and retrieval of data is effected through the use of SQL, ActiveX Data Object (ADO) and Open Database Connectivity (ODBC) driver[3].

The power supplies are situated at a sufficiently long distance from the control room. Hence, it is impracticable to have serial communication lines running from the control room to each of the power supplies. With a view to reducing the cabling requirement, all communication between the field-point devices (the power supplies in this case) and the computers residing at the control room is carried out over a high-bandwidth LAN.

In order to interface the LAN with the RS-422 serial communication link, we make use of an ADAM-4570 Ethernet to Serial Data Gateway. This device has two serial ports (which can be configured either as RS-232, RS-422 or RS-485 port) and an Ethernet port. We configure the ports for RS-422 communication since we wish to communicate with the power supplies using that standard. The device is placed close to the power supplies and serial communication cables are run between its serial ports and the power supplies. The Ethernet port of the device is connected to an Ethernet switch placed nearby. The console computer in the control room running the supervisory program is also connected to an Ethernet switch placed nearby (see Fig. 7). While running the installation utility of the ADAM-4570 module on the console computer, the serial ports of the module are mapped as (virtual) COM 3 and COM 4 ports of the console computer. All serial communication intended for the power supplies is now directed at COM 3 and COM 4 in the supervisory program, with the result that the intended data strings are written to (output) or read from (input) the remote serial ports. The TCP/IP communication that takes place between the console computer and the ADAM module is totally transparent to the supervisory program and the power supplies.

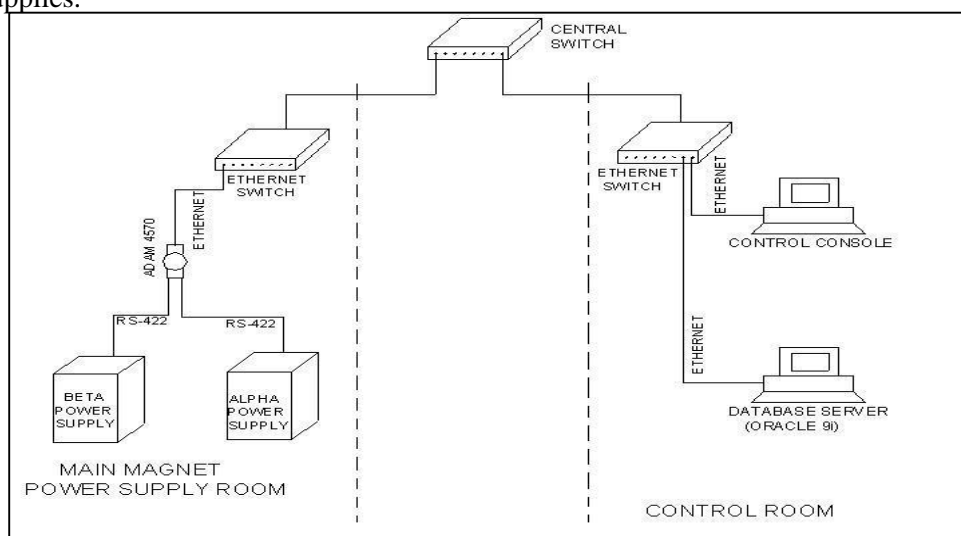


Fig. 7: Block schematic of the operation of the main magnet power supplies from the control room via LAN

## CONCLUSION

The scheme described above has been implemented around the K-500 superconducting cyclotron coming up at our Centre. The system has successfully worked during the energization phase of the superconducting magnet. In future, as and when new requirement arises, the control strategy would be suitably modified to meet the requirement. For example, the software (with modifications, if necessary) may form a part of the overall supervisory control system of the superconducting cyclotron [4].

## ACKNOWLEDGEMENT

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