T.1 Indus-2 magnet power supplies

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Introduction

In a particle accelerator, large numbers of electromagnets are used to bend, focus, and steer the beam of charged particles. To energize these magnets, various types of power supplies (PS) are required, such as DC, slowly varying, ramping and bipolar. The specifications of such power supplies are quite different from those of the conventional DC voltage power supplies. Accelerator power supplies are output current regulated so as to have tight control on the magnetic field created by the magnets. Magnet loads being highly inductive, store large amount of energy and hence need to be protected in the event of power failure or PS trip. Some of the magnets PS are required to operate in 2 quadrants or 4 quadrants, which require complex controls and configurations. In case a magnet uses multipole windings, each powered independently, PS encounters mutually induced voltage, which can affect output current if due care is not taken in the design. The power supply converter should have wide conversion range to facilitate large variation in output current. The output current stability and ripple requirements are tightly specified over long duration as the accelerators are operated continuously, even for weeks, without break.

For the Indus accelerators we have developed a wide variety of power supplies, the scheme to build up current in Indus- 2 runs as follows; The extracted electron beam from the booster (having energy in the range 450-700 MeV) is transported through transport line-3 (TL-3) and injected into Indus-2 through pulsed injection septums and kickers. Once the injected beam is stored in the ring, the injection cycles, are repeated till sufficient current is accumulated and there after the beam is ramped slowly to achieve the maximum energy up to 2.5 GeV. Indus-2 ring lattice consists of 8 unit cells, each cell having 2 bending, 9 quadrupole magnets and 4 sextupole magnets. TL-3 has 3 bending magnets and 18 quadrupole magnets. These magnets are energized through current controlled magnet power supplies. Also large numbers of steering and correction magnet power supplies are used in Indus-2 and TL-3 to control the beam position.

Indus-2 magnet PS are developed using different types of topologies and configurations depending on the load and output power, current range, polarity and stability requirements. Typical schemes include high power thyristor phase control, series pass control, fixed frequency phase shift pulse width modulation (PSPWM), variable frequency load resonant type etc. Power devices used include power rectifier diodes, SCRs, BJTs, IGBTs, MOSFETS etc., while the typical configurations cover full bridge, centre tapped, multi secondary etc.

Brief description, ratings, schemes and the safety features of the power supplies are reported in this article.

Specifications for DC power supplies

The specifications and number of the DC magnet power supplies required for TL-3 and Indus-2 are listed in Table T.1.1 and Table T.1.2 respectively.

Table T.1.1 Specifications of TL-3 magnet power supplies

Magnet Type	No. of magnets	No. of P/S	PS Current Min-Max (A)	PS Current Stability	Load R(Ohms)
1. Dipole Magnets					
a) Type BM-1	1	1	0-190	$\pm 5\times10^{-4}$	0.11
b) Type BM-2	1	1	0-190	$\pm 5\times10^{-4}$	0.11
c) Type BM-3	1	1	0-170	$\pm 5\times10^{-4}$	0.22
2. Quadrupole Magnets					
QD1,QF1,QD2,QD4, QF4,QD5,QF5,QD6,QF6	9	1	18-72	$\pm 5\times10^{-4}$	0.93
QF2,QF3	2	1	52-170	$\pm 5\times10^{-4}$	0.24
QD3	1	1	52-170	$\pm 5\times10^{-4}$	012
QF7,QD7,QF8,QF9,QD8,QF10	6	6	19-155	$\pm 5\times10^{-4}$	012
3. Steering Coils					
Steering coils	24	24	$\pm$ 10	$\pm 5\times10^{-4}$	0.7

Table T.1.2 Specifications of Indus-2 magnet power supplies

Magnet Type	No. of magnets	No. of P/S P/S	PS Current Min-Max. (A)	Stability	R(Ohms)	Load L (mH) LF	HF
Dipole magnets (including one reference magnet) all in series	16 + 1	1	200-900	$\pm 5x10^{-5}$	0.72	1615	1020
Quadrupole magnets Two Q1 magnets per cell (8 such cells) 2 magnets in series	2 x 8	8	30-180	$\pm 5x10^{-5}$	0.48	160	100
Two Q2 magnets per cell (8 such cells)	2 x 8	8	30-180	$\pm 5x10^{-5}$	0.66	240	160
Two Q3 magnets per cell (8 such cells)	2 x 8	8	30-180	$\pm 5x10^{-5}$	0.54	200	120
Two Q4 magnets per cell (8 such cells - all in series)	16	1	30-180	$\pm 5x10^{-5}$	4.35	1600	960
One Q5 magnet per cell (8 such cells- all in series)	8	1	30-180	$\pm 5x10^{-5}$	2.18	800	480
Skew quadrupole magnets	32	4	0-200	$\pm 1x10^{-3}$	0.1	-	-
Four sextupoles per cell (8 such cells - 16 in series)	32	2	40-230	$\pm 1x10^{-3}$	1.31	-	-
Steering coils	42 nos. CF+24SF 16 nosDP.	108 16	± 10 ± 10	$\pm 5x10^{-4}$ $\pm 5x10^{-4}$	1.5 4.2	200 400	

Indus-2 dipole magnet power supply

There are 16 dipole magnets in the ring and one in the power supply equipment room, all connected in series. The current is adjustable from 200 to 850 A. In order to achieve required performance, a low voltage series pass power supply is used in series with 12 pulse fully controlled thyristor converter. The power scheme is shown in fig. T.1.1. Two fully controlled thyristorized bridges B1 and B2 are fed by two isolated windings of a transformer separated by 30^0 electrical. These two bridges are connected in series to form a 12 pulse system. The power supply output voltage ripple requirement is very stringent, and is met by a damped LC passive filter and a series pass power supply. Freewheeling diodes are connected as shown in the block diagram. In order to further reduce the ripple on the magnets and for fast corrections due to sudden line changes, a series pass power supply of 20 V is added in series. This power supply is usually biased at 10 V and can vary between 0 to 20 V depending on rectifier output ripple. The control circuit or low level electronics is housed in a 19”, 4U sub rack.

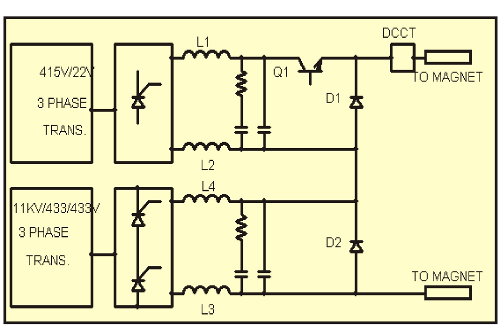

Fig. T.1.1 *Power circuit of dipole magnet power supply*

Indus-2 quadrupole magnet power supplies

There are five families of quadrupole magnets, namely Q1, Q2, Q3, Q4 and Q5 in each cell of Indus-2 ring. Out of 9 quadrupole magnets in each cell there are 2 numbers each of Q1, Q2, Q3, Q4 and one of Q5 type. Type Q1, Q2, and Q3 quadrupole in each cell are connected in series and are energized by a single power supply. All the Q4 and Q5 type magnets are connected in series and energized by a single power supply. In addition to these, skew quadrupoles are also used for beam correction. Power supplies for Q1 and Q2 type are developed using transistor series pass scheme with twelve-pulse SCR rectifier as pre-regulator. Q3 type power supplies are developed using high-frequency LCC resonant converter. Two Q3 type power supplies are housed in one cabinet. The power supplies for Q4 and Q5 have phase controlled twelve-pulse rectifier and LC passive filter plus an active filter. Skew quadrupole coils are fitted on 16 sextupole magnets. Total 4 power supplies (each feeding 4 skew QP coils) are required for these coils. These power supplies are developed using high-frequency resonant converter. Fig. T.1.2 shows the power scheme for Q1,Q2 and Q3 type power supplies. Fig. T.1.3 shows the schematic diagram for Q4 and Q5 type power supplies.

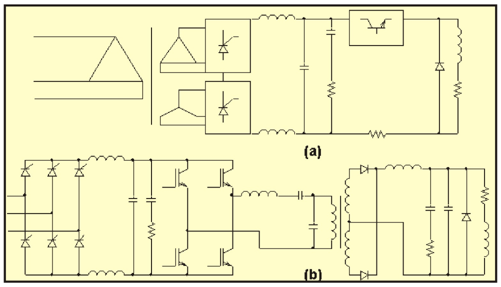

Fig. T.1.2 *Schematic circuit diagrams of (a) Q1,Q2 and (b) Q3 type Q-pole power supply*

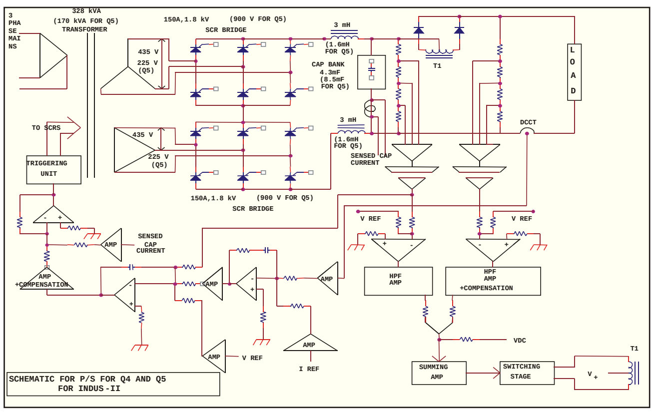

Fig. T.1.3 *Schematic circuit diagrams for Q4 and Q5 type Q-pole power supply*

Indus-2 sextupole magnet power supplies

There are two families of 16 sextupole magnets in the ring .All the sixteen magnets in each family are connected in series and energized by one power supply. The power supplies are developed using high-frequency three-phase LCC resonant converter. Two sextupole magnet power supplies are housed in one cabinet. Fig. T.1.4 shows the schematic of the power supply.

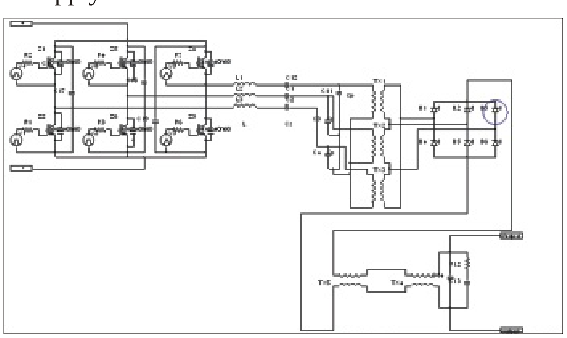

Fig. T.1.4 *Schematic circuit diagram for sextupole magnet power supply*

Transport line 3 magnet power supplies

The electron beam has to pass through transport line - 3 (TL-3) before reaching Indus-2 synchrotron. In this, the focusing of electron beam is achieved using quadrupole (QP) magnets. TL-3 magnet lattice has eighteen QP magnets which take electron bunches of 700MeV from the booster synchrotron and transport to 2.5 GeV synchrotron ring. In all, nine DC current power supplies feed these magnets. A six-pulse controlled rectifier feeds H-Bridge IGBT inverter operating at 25 kHz. Subsequently inverter output is rectified and filtered to give smooth DC load current. The SCR converter helps in inrush current control, and in the active damping of input filter. The capacitor put across the IGBTs also aid soft turn off of switches. Addition of two auxiliary chokes in the switching circuit enables resonant voltage transition even at light loads.The schematic diagram for TL-3 Quadrupole is shown in fig. T.1.5.

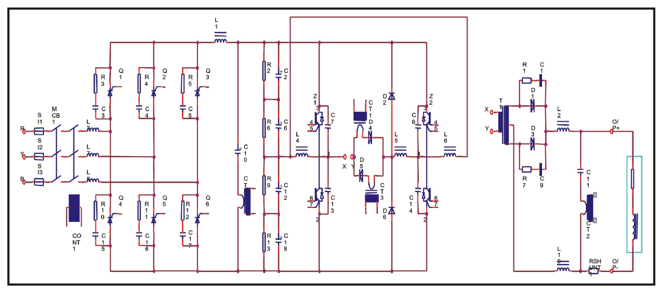

Fig. T.1.5 *Schematic circuit diagram for TL-3 Quadrupole Power Supply*

Pulsed magnet power supplies

In Indus-2, horizontal multi turn injection scheme is used. In this scheme a compensated orbit bump is produced and electron beam is injected parallel to the bumped orbit via septum magnet. Injection is to be carried out in the first long straight section, LS-1. The compensated bump is produced by using four kicker magnets. A half sine wave type of current pulse has been fixed for Indus-2 kicker power supplies. Injection will take place around peak value of sinusoidal current. Base width of half sine current has been decided to be 3 msec. The specifications of pulse magnet power supplies for Indus-2 is given in Table T.1.3. The septum magnets require half sine wave current pulse. These pulses are generated by discharging a bank of energy storage capacitors into the inductive load of septum magnet via a thyristor switch to form an under damped LCR circuit. The injection of bunches takes place at the peak (flat top) of the half sine wave. A bank of energy storage capacitors has been realized such that the series inductance of the circuit remains low. Eight RG-8/U cables form flexible connection link between power supply and magnet. The whole arrangement was made coaxial to reduce stray inductance. The schematic diagram of kicker magnet power supply is shown in fig. T.1.6.

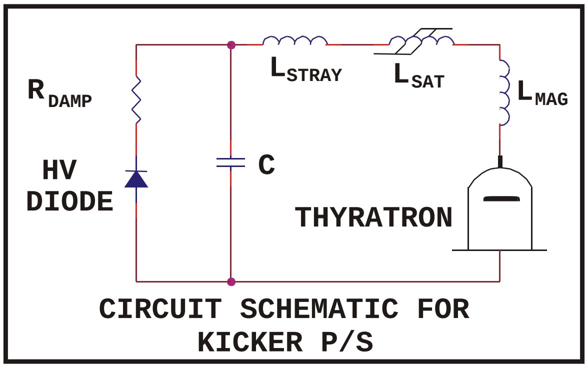

Fig. T.1.6 *Schematic diagram of kicker magnet power supply*

Correction coil power supplies

Correction coil power supplies are used to energize the correction magnets to correct the beam if it deviates from its orbit. Salient features of these power supplies are: unity power factor at the input, bipolar load current ability with smooth transition from one polarity to other, higher load current stability and higher efficiency. Power stage of the power supply consists of a boost converter in the input to ensure unity power factor, a full-bridge inverter to achieve isolation as well as required voltage at the load followed by full bridge inverter for changing polarity of the load current. The schematic diagram of the correction coil power supply is shown in fig. T.1.7.

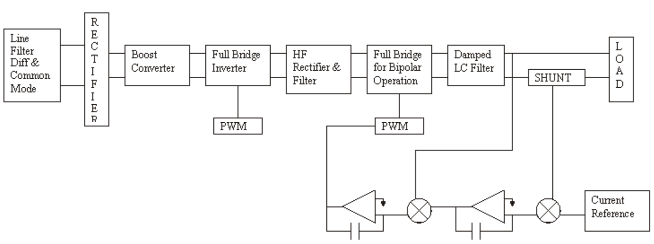

Fig. T.1.7 *Schematic diagram of correction coil power supply*

Achieving high performance

Most of the power supplies have stringent requirement of long term current stability, which is as high as ± 50 ppm. Noise mitigation techniques were used in high frequency switched converters to achieve the required stability. Typical control loop of the power supply consists of two loops: the inner fast voltage loop corrects input line variation and outer slow current loop caters for temperature variation in load. The output current is sensed using highly stable DCCT (temperature coefficient < 1 ppm/°C). The front-end control circuit is placed in a temperature-controlled oven to minimize temperature drift in amplifiers. Protections like over voltage, over current, over temperature, low water flow rate, earth fault, over ripple current, open load etc. are incorporated. The power supplies can be operated in local/remote mode. Typical long-term current stability performance is shown in fig. T.1.8.

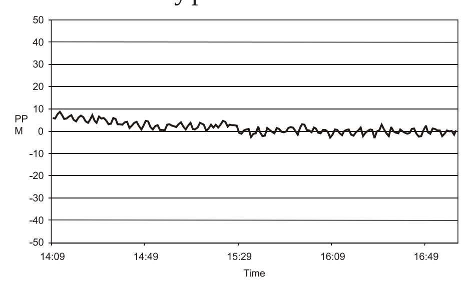

Fig. T.1.8 *Long-term stability results for Indus-2 quadrupole magnet power supply*

Conclusion

All the power supplies for Indus-2 have been designed by power supply group and fabricated indigenously. Most of these power supplies have been tested with the actual magnet loads. The remote testing from control room is in progress. Power supplies division has successfully developed large number of power supplies with different types ranging from linear to high frequency, DC to pulsed, low power to high power and high current stability.

Table T.1.3 Specifications of pulsed magnet power supplies

S. No	Parameters	Kicker power supplies	Thin septum magnet power supply	Thick septum magnet power supply
1.	Magnet Inductance	0.82mH	0.95 µH	2.7 µH
2.	Pulse shape	Half sine wave, 03 msec base width.	Half Sine	Half Sine
3.	Current Amplitude	11,000 Amp	5300 A	8500 A
4.	Current Stability	± $1X10^{-03}$	±100 ppm	±100 ppm
5.	Jitter	± 20 nsec	±100 nS	±100 nS
6.	Deflection	± 25 mrad.	2°	19°