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60 *Abstract :* Electromagnetic Manufacturing (EMM) process is the state of art technology for shaping and joining of metals based on EM Forming and Welding. In this process, forming and welding are achieved without physical contact between tool and job piece, and hence has merits over conventional processes such as brazing and welding. A 20kV, 40kJ EMM machine has been designed, fabricated, assembled, and tested. The machine consists of a capacitor charging power supply, four modular type capacitor banks, strip line and coaxial cable delay line connections, trigatron spark gap switches, solid state trigger supply and PLC. Electromagnetic manufacturing tools (strong coils and field shapers) have been developed for forming and welding applications.

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सार

ईएम फॉर्मिंग और वेल्डिंग पर आधारित धातुओं को आकार प्रदान करने और जोड़ने की एक अत्याधुनिक प्रौद्योगिकी विद्युतचुंबकीय विनिर्माण (ईएमएम) प्रक्रिया है । इस प्रक्रिया में, औजार और वेल्ड की जानेवाली धातु (जॉब पीस) के बीच बिना किसी वास्तविक संपर्क के फॉर्मिंग और वेल्डिंग कर ली जाती है और इसलिए यह ब्रेजिंग और वेल्डिंग जैसी पारंपरिक प्रक्रिया से बेहतर है । एक EMM यंत्र 20kV, 40kJ का अभिकल्पन, संविरचन, संयोजन और परीक्षण किया गया है। इस यंत्र में विद्युत आपूर्ति को आवेशित करने वाला चार मॉड्युलर आकार का कैपेसिटर बैंक, स्ट्रिप लाइन एवं समाक्षी (कोएक्सियल) केबल पर आधारित डिले लाइन संयोजन, ट्रिगेट्रॉन स्पार्क गैप स्विच, ठोस अवस्था ट्रिगर आपूर्ति एवं पी.एल.सी. शामिल हैं । विद्युतचुंबकीय विनिर्माण औजारों (मजबूत कुंडली एवं फील्ड शेपर्स) को फॉर्मिंग एवं वेल्डिंग अनुप्रयोगों के लिए विकसित किया गया है ।

20kV, 40kJ Electromagnetic Manufacturing Machine

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Abstract:

Electromagnetic Manufacturing (EMM) process is the state of art technology for shaping and joining of metals based on EM Forming and Welding. In this process, forming and welding are achieved without physical contact between tool and job piece, and hence has merits over conventional processes such as brazing and welding. A 20kV, 40 kJ EMM machine has been designed, fabricated, assembled, and tested. The machine consists of a capacitor charging power supply, four modular type capacitor banks, strip line and coaxial cable delay line connections, trigatron spark gap switches, solid state trigger supply and PLC. Electromagnetic manufacturing tools (strong coils and field shapers) have been developed for forming and welding applications.

Keywords: Electromagnetic forming/welding; Energy storage capacitor bank; Skin depth; Trigger generator; Capacitor charging power supply, Trigatron type spark gap switch, Strip line; Delay line; PLC, HMI, EMM tool

CONTENTS

1. General Description

1.1 Introduction

Electromagnetic Manufacturing (EMM) process is the state of art technology for shaping and joining of metals based on Electromagnetic Forming (EMF) and Electromagnetic Welding (EMW). These techniques are based on Lorentz force to achieve the required goal. The force is generated when a high voltage charged capacitor bank discharges through a forming/displacement coil placed in the proximity of work piece. The force developed is on account of interaction of induced current in the work piece with the magnetic field produced by the coil. In these techniques, forming and welding are achieved without physical contact between tool and job piece. Hence it has obvious merits over conventional processes such as brazing, welding, expansion, contraction, contour formation etc., when used for some special applications. This sophisticated technique has many advantages such as precision, reproducibility, high production rate, no tool marks, minimization of manual error, automation ease, etc. The preparatory procedures such as preheating, lubrication, etc. are not needed. Since the bond is achieved by impact/pressure, this method is ideally suited for joining/welding of dissimilar metals with large difference in their melting points. This added advantage is generally not available in the conventional processes. This technique has applications in automobile, electric, defense, aeronautical and other industries. Moreover, it has tremendous potential for use in the manufacture of appliances and consumer products.

A 40 kJ, 20 kV capacitor bank comprising of four modules has been designed, fabricated, assembled and tested as a basic building block of the pulse power system for these applications [1]. The physical layout of the bank is also made to provide low inductance highly compact modules while providing access for maintenances and repair.

The 40kJ, 20kV Electromagnetic Manufacturing Equipment consists of four energy storage capacitor based sub-banks. Capacitor charging power supply (CCPS) based on constant current power source is employed for high efficiency and compact size. Single trigatron type spark gaps (TSG) are employed as switches [2]. Four switches are used, one for each sub-bank. A trigger generator provides four simultaneous synchronized trigger pulses for firing the spark-gaps when master trigger command is actuated through PLC. Measurement is provided on HMI panel to indicate the status of various subsystems of the Energy Storage Capacitor Bank. A HV dump switch is provided for conditioning of capacitor bank and also when pulse power is not required to be transferred to the load coil. Dump resistors are air cooled. Since the capacitor banks are modular in nature the system can be configured to operate in 10, 20, 30 and 40kJ.

All the system racks are properly grounded for safety and also to reduce ground loop Electromagnetic Interference (EMI). The 40kJ, 20kV equipment can be used for forming and welding applications. The Electromagnetic Forming / Welding (EMF/W) is achieved by a helical coil / flat/spiral/ depending on the geometry of the job. The feasibility of EMF/EMW technology has been demonstrated for many in house and general applications by APPD, BARC and the competence has been firmly established. The main advantages of EMF/W over conventional techniques are as follows:

a) Repeatability: The electromagnetic pulse can be controlled to high degree of accuracy and hence the forming is highly repeatable. The limitations in reproducibility are due to inaccuracies in job alignment.

b) Ease in operation: The operation of the equipment is simple which consists of charging and discharging of capacitors. The equipment can be operated by single operator and automation is provided by a PLC control system.

c) No Tool marks: In electromagnetic forming process, the pressure is developed without physical contact. Hence the process does not require lubrication and leaves no tool marks.

d) Strength: The joints made by this process are stronger than the parent material unlike in all the other processes. Hardening takes place due to high strain rate forming, which is favorable.

e) High speed of operation: The speed is limited by the time required to load and unload the job piece. For fast production rates, proper clamping, holding and aligning devices are required.

f) No spring back: During the process of forming, the material is impact loaded into plastic region, resulting into permanent deformation. Hence there are no spring back effects.

g) Minimum tooling cost: Field shapers can be used along with the machine and forming coil. Jobs of different geometry and material can be formed by changing the energy, coil and/or the field shaper. This can bring down the tooling cost considerably.

h) Preparatory procedures not needed: The EMF process being a non contact method, the preparatory procedures such as lubrication, cleaning are not required.

i) Ease of automation: Due to elimination of preparatory methods, the forming can be achieved in single step. The automation becomes easy because of elimination of manual procedures.

Pulse power technology world over is gaining importance in the industrial, defense, food, environment and medical sectors with diverse applications, e.g., electromagnetic forming, radar, EM launchers, food processing, exhaust gas treatment are just a few to mention. The primary energy source, invariably for most of the applications, is a well configured energy storage capacitor bank to suit the required application. In India, BARC have taken the lead to develop this technology. The main objective was to meet the immediate in-house special requirements of the nuclear industry, which could not receive equipment from the countries who owned the technology because of export control regime. It was also realized that our industries would make use of the indigenously developed advanced technology.

1.2 System Specifications

(1) Energy	: 40kJ, 20kV
(2) Modules/Capacitor Bank	: 4 Modules. Each Module consists of 4 Nos. of 14μF, 20kV, Energy Storage Capacitor
(3) Peak Short Circuit Current	: 350kA (maximum)
(4) Capacitor Charging	: Charging Time: 45sec
(5) Repetition Rate	: Minimum one Discharge in every five minutes
(6) Controls and Monitoring	: (a) PLC & HMI Controls (b) Mains 'ON' (c) DUMP 'ON' (d) HV 'ON' (e) CHARGE 'ON' (f) Module (sub bank) Voltage setting and Indication (g) Charging time (h) Shots Counter (i) Discharge current through Current Shunt monitored on Oscilloscope
(7) Protection	: (a) Mains Fuse (b) Incoming Circuit breaker (c) Over Current and Short Circuit Current protection

	of charging power supply
(8) Safety	: (a) Energy Dump of capacitor bank
	(b) HV Danger Board
	(c) Auto Dump / Charge prevention when rack is open
	(d) Grounding using copper bus bars.
(9) Life	**:** (a) Capacitor: 50,000 Shots (at 80% reversal of under damped oscillations).
	(b) Spark gap switch: 10,000 shots.
(10) Power Supply	**:** Input**:** 415V, 3 phase, 15 Amp, 50 Hz,
	: Output: 0 to 25kVDC, 200 mA CCPS
(11) Temperature	**:** 10°C to 45°C (operating)
(12) Equipment Size	: Power Supply & PLC controls (0.8 x 0.8 x 2.0 M)
	Capacitor rack (1.2 x 1.2 x 2.0 M);
	EMM tool rack (0.8 x 0.8 x 2.0 M)

2. System Design and Development

2.1 Design of Energy Storage Capacitor Banks (ESCB):

Importantly, the design basis of any engineering system are application driven, but when the number of applications tend to become large, as is the case with energy storage capacitor bank technology, it is difficult to generalize the design basis. Still, looking at the wide range of applications world over, capacitor banks are catering to, one can summarize the following broad basis:

(i) High capacitance, low voltage ESCB (> 500 μF, < 10 kV)

(ii) Medium capacitance, medium voltage ESCB (> 10 μF but <500 μF and > 10 kV but < 50 kV)

(iii) Low capacitance, high voltage ESCB (< 10 μF, > 50 kV).

Each of the aforementioned categories has its distinct design basis. The following is a brief description of their design philosophy.

2.1.1 High Capacitance, Low Voltage ESCB

(CAPACITANCE: > 500 μF, VOLTAGE: < 10 KV)

(a) These banks are also termed as slow banks as invariably they feed large inductive loads, e.g., an electro-magnet system or an inductive energy storage system and thus have current rise times in 10s of milliseconds [3, 4].

(b) As far as design challenges go, these banks do not offer much difficulty. Load currents are small (few kAs) and the switching devices should be able to take large coulombs. Ignitrons are the best suited switches in these applications.

2.1.2 Medium Capacitance, Medium Voltage ESCB

(CAPACITANCE: > 10 μF BUT <500 μF AND, VOLTAGE: > 10 KV BUT < 50 KV)

(a) These banks cater to the widest industrial applications. Electromagnetic forming/welding, magnetizers/demagnetizers, lightning current generators, electro-magnetic guns/launchers etc., are some important applications in this category. The designs tend to become more challenging as one goes high in voltage and low in capacitance. This has direct bearing on shorter rise time requirements one has to meet besides catering to larger load currents. Typically, loads are inductive in the range of 10s to 100s of μH leading to current periods of 50 to 100s of microseconds with current magnitudes of 100s of kAs. Few switching devices excepting triggered spark-gap switches, meet these requirements. The ESCB technology, described here falls under this category.

(b) The general challenge, while designing capacitor banks in this category, is to conceive of low inductance bank configurations and low inductance lead connections. Some design philosophies while configuring low inductance configurations are

(i) Strip-line geometry, and

(ii) Co-axial geometry.

(c) Amongst the two geometries, strip-line configuration, perhaps, offers the lowest inductance configuration, as would be clear from the following formulae of inductance per unit length in the two categories:

$$L \text{ (Strip line)} = \mu_0 \text{ x } H/W \text{ H/m} \quad (2.1)$$

Where, H is the separation between the line conductors and W is the width of strip line conductors. μ_0 the permeability of air ($4\ \pi \text{x } 10^{-7}$ H/m).

$$L \text{ (Co-axial)} = (\mu_0 / 2\pi) \text{ x } \ln \text{(OD/ID)} \text{ H/m} \quad (2.2)$$

Where, OD is the outer diameter of the co-axial geometry and ID is the inner conductor diameter of the co-axial geometry [5].

(d) From the above equations, it is simple to reduce H in case of strip line by employing high grade insulating medium, e.g., mylar, polypropylene etc., and increase the conductor width, to significantly reduce the system inductance per unit length, but the same is not true while configuring the co-axial geometry as the two co-axial conductors tend to become close, the intensification of fields on the inner conductor becomes limiting factor.

(e) Co-axial geometry, on the other hand, has advantages in confining the fields within the bounds of the external conductor and the system tends to have better EM noise suppressing capability during switching instances. This becomes important during fast and large current switching. In addition, invariably, as the bank capacitors tend to occupy large volumes because of their poor energy density, configuring them in strip-line geometry is much more difficult than in the co-axial geometry. Specially configured plastic/metal case capacitors are developed to arrange them in strip line geometry.

2.1.3 Low Capacitance, High Voltage ESCB

(CAPACITANCE: < 10 μF AND, VOLTAGE: > 50 KV)

(a) Designing these banks offer the greatest challenges. The applications typically confine to creating extreme energy density within the confines of R&D laboratories. Components have to be specifically configured for low inductance values. Capacitors in these banks have individual self inductance value as low as 20 nH and are specially developed. The National Ignition Facility, USA experimenting with the laser target fusion, has these capacitors specially developed from General Atomics, USA (Earlier Maxwell Inc., the leading manufacturer of low inductance special capacitors). Geometrical layout is close to strip line for achieving low over all inductance values.

(b) These ratings do not fall within the purview of commercially required banks and hence not much of further consideration.

2.2 System Design Considerations:

The Energy Storage Capacitor Bank (ESCB) system is designed as medium capacitance and medium voltage, to provide maximum output ratings of Voltage: 20 kV and Energy: 40kJ. The parameters and the components are selected as follows:

2.2.1 ESCB Voltage Selection: The charging voltage required for 40 kJ ESCB is limited to 20 kV with the following considerations. The 40kJ ESCB Bank is to be used in Industrial applications. Also to deliver maximum current to the load coil, the connecting lead inductance has to be as small as possible, taking into consideration the required voltage insulation. The voltage ratings are kept within 20kV or below to avoid corona discharges as well as to take care of operational safety. Higher operating voltages beyond 20kV will require higher gaps between connecting leads resulting in high inductance and lower load (coil) current which is not acceptable. Lower voltage below 20kV leads to higher capacitance of the ESBC for the same energy. This higher capacitance will lead to lowering of the frequency below 10 kHz and poor coupling for the job. The 40kJ bank is designed based on indigenously available energy storage capacitors. Energy storage capacitors in the range of 20kV, 14µF/20kV, 18µF are commercially available. Capacitors available in this range are highly reliable and have long life as proved by our laboratory experience.

2.2.2 Calculation of System Capacitance: Using input parameters viz, maximum charging voltage (20kV dc) and Energy (40kJ); total system capacitance can be calculated by following energy relation:

$$E = \tfrac{1}{2} CV^2 \tag{2.3}$$

Gives 'C' value of 200μF

The other constraints are: (a) 20kV Capacitors are available in 14 μF and 18 μF capacity, and (b) the capacitors should not be operated beyond 90% of rated energy capacity to increase its operating life. Accordingly 16 nos. of 14 μF capacitors have been chosen. For 40 kJ energy the total capacitance of the bank works out to be 224 μF.

2.2.3 Operating Frequency: The 40kJ, 20kV system operating frequency is in the range of 7-10 kHz can perform most of the EMF/EMW jobs. System frequency is governed by the following factors.

(i) Upper limit of system frequency is determined by system inductance which cannot be reduced below a certain minimum level dictated by the lead inductance and the capacitor inductance.

(ii) Lower limit is determined by current skin depth, which in turn limits the minimum thickness of job to be formed/welded (In general job-piece thickness should be equal to or more than current skin depth for effective utilization of imparted force).

Current skin depth (metre) is given by:

$$\delta = \left(\frac{\rho}{\pi f \mu_0}\right)^{1/2} \tag{2.4}$$

Where f = system frequency and μ_0 = Permeability of system μ ($4\pi \times 10^{-7}$ H/m),

ρ = resistivity in Ohm-m. Taking minimum thickness of 1 mm for the aluminum job-piece to be formed / welded we get system frequency from equation (2.4) as 7 kHz. It means system frequency should not be less than 7 kHz to be used for forming/welding of 1mm aluminum sample. Lower limit of the system frequency is set to 7 kHz.

Upper limit of system frequency is governed by configuration of system. EMF/W systems are configured in a manner to reduce the overall inductance to a minimum possible level which enhances the peak current delivered by the system to the load coil. To achieve this self inductance of capacitor should be as low as possible. However practical value of self inductance of the each energy storage capacitor lies around 100 nH. The estimated value of total inductance offered by parallel combination of 16 numbers of capacitor (224 μF) is of the order of 8 nH. Inductance offered by the four spark gap switches reduces the net inductance to ~ 10 nH which is one-fourth of that of a single spark gap switch. HV strip line bus bars are connected to spark-gap switches fixed on top of the ESC banks. Load coil connection is taken from the other end of the strip line through delay line cables. Strip line is formed by using 50 mm wide, 2mm thick nickel coated copper plates and 6mm thick grounded aluminum plate, with 3mm thick polypropylene sheet insulation (ε_r: 2.5). All the corners of plates are rounded off to avoid any corona discharge or flashover. The inductance of strip-line arrangement is given by Eq (2.1). Based on dimensions of the assembly lay-out, total overall inductance offered by strip lines and transmission line cable assemblies is 157 nH. Total overall inductance of the system excluding that of coil is about 175 nH. The EMF/W coil inductance is 1.4μH without field shaper and 1.0μH with field shaper and job. The approximate operating frequency (neglecting damping resistance) is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2.5}$$

The ringing frequency of the system is around 10 kHz.

2.2.4 Peak Current Rating: The short circuit peak current at 20 kV exceeds 300 kA as per the above calculation. For the 40 kJ, 20kV EMF/EMW system, the total system inductance including load coil is 1.57μH (without field shaper) and 1.175 μH (with field shaper and job). The current delivered to the coil is determined by following relation:

$$1/2\ LI^2_{peak} = 40\ \text{kJ} \tag{2.6}$$

The peak current I_{peak} = 260 kA

2.2.5 Capacitor Selection: Energy rating of each 14μF capacitor is 2.8 kJ at 20kV charging voltage. In order to achieve 40kJ energy the ESBC is made by paralleling 14μF/20kV capacitors. These 14μF/20kV capacitors are commercially available. The energy range of 2.5-5kJ per can enclosure is easy to handle. In case of any fault the 4 mm thick non magnetic steel casing can withstand the fault without rupture.

To achieve 40kJ energy rating, 4 sub-banks each consisting of four 14μF/20kV capacitors are connected in parallel. This arrangement is necessary for the safety of capacitors. Generally the can withstanding capability is rated at ten times the fault energy of capacitor. In any case energy in capacitor should not go beyond its fault energy. In case of a fault, other capacitors of the same sub bank may discharge into the faulty capacitor. Keeping this in consideration, only 4 capacitors are connected in a sub-bank. The size of a 14μF/20kV capacitor manufactured and supplied by M/s Yesha Capacitors Ltd, Baroda is 265 mm (W), 250 mm (D), 690 mm (Ht). The size of a 14μF/20kV capacitor manufactured and supplied by M/s Magnewin Ltd, Sangli is 265 mm (W) x 240 mm (D) x 650 mm (Ht). However, single capacitor equivalent to the capacitance of the parallel combinations was not considered in our design due to bulky size and handling problems of the single equivalent capacitor. Another important consideration in selection of four sub banks is the life of the spark-gap. The life is governed by accumulated coulombs discharge through the spark gap switches. All four sub-banks discharge through their respective spark gap. Hence it leads to enhanced life of the spark gaps resulting from distribution of the accumulated charges. It also reduces the frequency of spark gap maintenance. Four sub banks have been chosen for 40kJ energy requirement. As increase in the number of sub banks increases the number of trigger pulses to be generated; this leads to increase in the hardware requirement of the switching system. Hence a tradeoff is reached between the frequency of maintenance of the switches and the switching system. Modular construction of 40kJ/20kV system permits modular operation with variable energy/ frequency as per the user's applications.

2.2.6 Spark-Gap Switches: The switches used in these banks, should be able to withstand high voltage and able to conduct high current and large charge transfer. They should also be able to switch on within few tens of ns and should have a life exceeding 1000 discharges. Table 1 shows the comparisons of various switching devices. These specifications rule out the use of currently available IGBTs, SCRs, Ignitrons, Thyratrons etc. the only suitable switches are spark gaps. However spark gaps also have a limited current and charge transfer capacity and their inductance is relatively high (several tens of nH). Therefore several spark gaps are employed in parallel to get specified current/charge capacities. A comparison of BARC makes and e2V make spark gaps are shown in the Table 2.

A total of four spark-gap switches are used. One spark gap switch is mounted over each sub-bank of four capacitors. In case of triggering 1.1 Coloumb (Q = I*t) of charge is passing through every spark gap switch at 20kV. A gap of 6 - 8 mm is maintained between spark gap electrodes (SS304) depending on the operating voltage. Charge life of the spark gap switch is of the order of 10,000 Coulombs. In present system ~1.1C of charge/shot is passing, giving a very good life of 10,000 shots.

Gas purging system has employed for spark gap switches (4 nos.) to increase the reliability of spark gap during operation in terms of breakdown voltage and triggering. Gas purging system comprises of solenoid valves (2nos.), manifold using PU tubing, relay (230 V AC), N_2 gas cylinder. Before and after operation of the capacitor bank, spark gap switches are purged using IOLAR grade nitrogen gas. Purging operation is performed from HMI unit located on remote control rack.

2.2.7 Dump Switch: Dumping of Energy Storage capacitor bank energy into the dump resistors by HV ITT Jennings vacuum contactor. The main contactor is actuated by solenoid coil along with two SPDT switches (230V AC, 15A rms) mounted in the base of the unit via a light weight insulating rod. One of the SPDT switches is used as interlocking to enable the charging of Energy Storage Capacitors by enabling the HV ON. The main contacts of the vacuum contactor are in normally closed (NC) position. Being the main HV contacts in NC position has the advantage of dumping the stored energy in case of main supply failure automatically and also interrupting the charging circuit. The model number of dump switch is RP900L that can make/break contacts at 50kV, 200A (rms) and can be actuated by 230V, 50Hz supply. It is capable to discharge capacitor discharge decaying current (0 to 200µs) up to 100kA. Its contact resistance, capacitance and inductance are 0.0005Ω, 5.5pF and 45 nH respectively. The contactor has operation life of the order of 10^5 make-breaks.

TABLE-1

Comparison of semiconductor, thyratron, spark gaps, ignitron and triggered vacuum switches

S.No.	Parameter	Semiconductor	Thyratron	Spark gap	Ignitron	Triggered Vacuum Switch
1	hold off voltage	6 kV	50kV	Vast hold off range due to flexibility in gas pressure and Electrode spacing (20 to 100kV)	20 to 100kV	5 to 15kV
2	trigger voltage	<100V	200 to 1500V	Usually Equal to Hold off voltage	200V to 4kV corresponding closing times from 100μs to sub-microsecond.	1kV to 7.5kV
3	jitter		1 to 5ns	50 ns		
4	switching time		15 to 40ns	5 ns	>50 ns	
5	pulse repetation rate		10kHz	100Hz	Low Rep Rate (2pulses/minute)	
6	operating pressure		0.3 to 0.5torr Hydrogen gas	Atmospheric to 3 to 4 times more depending upon gas, electrode spacing and holding voltage	Low vapor pressure 0.0012torr Mercury	$<10^{-4}$ torr
7	current rating	2-3 kA	In the range of kA	Generally higher(10's of kA to 100kA)	5 to 500kA, low forward drop (20 to 30V)	5kA to 75kA
8	shot life	10^6	10^8 to 10^9	Expressed in Coulombs (5000 to 20,000Coulombs)	Expressed in Coulombs (400 Coulombs)	Expressed in Coulombs (1000 Coulombs)
9	Reversal	Unidirectional	Unidirectional	Bidirectional (>80% reversal)	Unidirectional (~20 to 30% reversal)	Bidirectional (>80% reversal

TABLE-2

Comparison of BARC and e2V make spark gaps

S.No.	PARAMETER	e2V Manufactured [*] Three-Electrode Triggered Spark Gaps		BARC Single Trigatron Spark Gaps [1,2]	
		GXT Series	GXG Series	Spark Gap 1	Spark Gap 2
01	Sealing	Ceramic Body Hermetically sealed	Ceramic Body Hermetically sealed	Atmospheric With Perspex Insulator	Atmospheric With Delrin Insulator
02	DC Hold-off Voltage (kV)	5-38	15-50	3-20	5-50
03	Operating Voltage Range (kV)	5-32	15-40	3-16	5-40
04	Trigger voltage (kV) [#] With >15kV/μs	5kV	15kV	~22kV	~22kV
05	Peak Current in single discharge (kA)	100	140	250	250
06	Charge Transfer in single discharge (C)	0.5	0.5	4	7
07	Repetition Rate (pps)[$]	<100	<100	<20	<20
08	di/dt (kA/s)	<125	<125	<125	<125
09	@ Shot life	10000	10000	2000	2000

* e2V technologies (UK) limited (www.e2vtechnologies.com)

Open circuit peak amplitude

$ The repetition rate of trigger circuit is 20 pps max,

Spark Gap-1: Developed and used in 10kJ,10kV EM Welding Set-up

Spark Gap-2: Developed and used in 40kJ, 20kV in ESC Banks

@ The shot life is arrived from experimental data.

2.2.8 Trigger Generator: The EMM system consists of four sub-bank of 10kJ each. Each sub bank discharges through their respective single trigatron type switch into the load coil. Four numbers of pulses are used to fire four single trigatron type switches. These trigger pulses are generated by simultaneously discharging four numbers of low inductance capacitors into the primaries of the four pulse transformers, by firing a master IGBT switch (SEMIKRON IGBT type SKM800GA176D) controlled through fiber optic and driver circuit. Integrated circuit board supplied by M/s ECIL using M57962L (hybrid integrated circuit) is used for driving a n-channel IGBT module. This device operates as an isolation stage for these modules and provides electrical isolation (2.5kV rms for 1 minute) between the input and output with an opto-coupler. Short circuit protection is provided by a built in desaturation detector. The fault signal is provided for controls, if the short circuit protection is activated. The M57962L based integrated circuit board is used to drive the IGBT driver booster card which in turn is used to drive IGBT module (1700V, 800A). The circuit diagram of the solid state trigger generator is shown in Appendix C4. Trigger capacitors (3µF, 1kV) are charged to 650V DC by half Wave voltage doublers through resistors (10 kΩ/2W, 4 Nos.). The stored energy in the trigger capacitors are discharged into the primaries of Met-Glass core pulse transformer (2:75, 4 nos.) through the IGBT switch. The input to the driver circuit is fed from a standard PLC unit through fiber optics transmitter (HFBR1521Z) and receiver (HFVR2521Z). Isolation capacitors (1200pF, 30kV, ceramic) are connected in between the four pulse transformer secondaries. These capacitors isolate the trigger circuit during discharge of ESC sub-banks. RG 58 coaxial cables are used for discharging the trigger capacitor energy into the primaries of the pulse transformer to improve trigger pulse rise time. Output pulse of 10kV across spark gap, 100ns rise time is obtained between spark gap electrodes and trigger pin. After “End” of charge, if the Trigger button is in auto mode, the charged capacitor bank will be triggered automatically within pre set time. When the trigger push button is in manual mode, the trigger button should be pushed after end of charge to trigger the capacitor bank spark gap switches.

Voltage doubler is used to generate 650V DC to power the IGBT. Filter capacitors (15µF/450 V x 2 numbers) are used for stabilizing the output dc voltage. Bleeder resistor of 880kΩ/10W is used for discharging the capacitor when circuit is switched OFF.

2.2.9 Coaxial discharge Cable: The coaxial cables used for capacitor bank discharge system must be capable of handling large currents with minimum power loss. Four high voltage coaxial cables (Model: 2297) are used to transmit the discharge current of 40kJ energy storage capacitor bank to load coil. The cable is selected as it has low inductance of 126 nH/m and cross section area of 22.34mm2. Under normal operation each cable can carry 75kA (max.) discharge pulse current. The cables will be tested using 40 kJ capacitor bank by connecting them to the load, and gradually increasing the charge voltage.

2.3 System description and layout:

The overall schematic block diagram of 40kJ, 20kV system is shown in Fig.2.1. In the energy storage capacitor bank, large number of energy storage capacitors are connected in parallel and charged to a DC voltage up to 20 kV by means of a capacitor charging power supply (CCPS) [6]. The energy is transferred to the load coil by a closing switch (Spark gap). A trigger command generated by multiple trigger pulse generator is used to close the switch.

Each sub-bank contains four capacitors. Single trigatron type spark gaps are used as switches. Four numbers of switches are used, one for each sub-bank. A trigger generator generates four simultaneous trigger pulses for firing the spark-gaps, as and when master trigger command is actuated. Meters are provided on control panel to indicate, output voltage of CCPS power supply and individual sub-bank voltages. A PLC is employed for data acquisition and control. A vacuum dump switch is provided which is used during conditioning of capacitor bank and also when it is required not to transfer the power to the load coil. The variable CCPS (0-25kV) is used to charge the capacitor bank. All energy storage capacitor sub-banks, charging/dump resistors and controls are housed in an MS rack mounted on wheels. Charge and dump resistors are air natural cooled. All the racks are properly grounded for safety and also to reduce ground loop Electromagnetic Interference (EMI). For this single point ground pit (0.2 Ω Resistance) is used. Details of each block are given below. The energy is transferred to the load coil by a closing switch (Spark gap/Ignitron). A trigger command generated by multiple trigger pulse generator is used to close the switch.

The salient features of each block are given below.

2.3.1 Control Panel (PLC based)

a) Power line input-ON/OFF using MCCB switch.

b) High voltage CHARGE ON using HMI panel.

c) High voltage Setting using HMI panel.

d) Dump switch ON/OFF using HMI panel.

e) Trigger operation ON automatic through PLC unit else using HMI panel

f) Shot counter- Electronic on HMI panel

h) Capacitor bank charging voltage indicators-4 Nos. on HMI Panel, one for each sub-bank.

i) Charging Time.

j) Panel door-closed indicating lamp (Optional).

k) Panel input supply ON on HMI Panel

l) Power supply overload protection

m) Power line filter, to ensure power supply as electromagnetically compatible located in Power supply rack.

n) A 200MHz (2GS/s) DSO is mounted in this control rack to monitor the discharge current.

2.3.2 Capacitor Charging Power Supply

a) Input: 415V, 3 phase, 2 A, 50Hz, A.C.

b) Output: 25kV, 200 mA

c) Capacitor bank charging time: Approx. 45 seconds

2.3.3 Dump Resistors

Dump Resistor: 75 kΩ, 500W

Wire wound Resistor Stack (3 x 25 kΩ, 100 W each each, in Series per stack);

Total 2 stacks, two stack per sub- bank

2.3.4 Energy Storage Capacitor Bank

Four 20kV, 10kJ modules, each module consists of three 14 μF, 20kV, 2.8kJ energy storage capacitor. Total capacity equals to 224 μF.

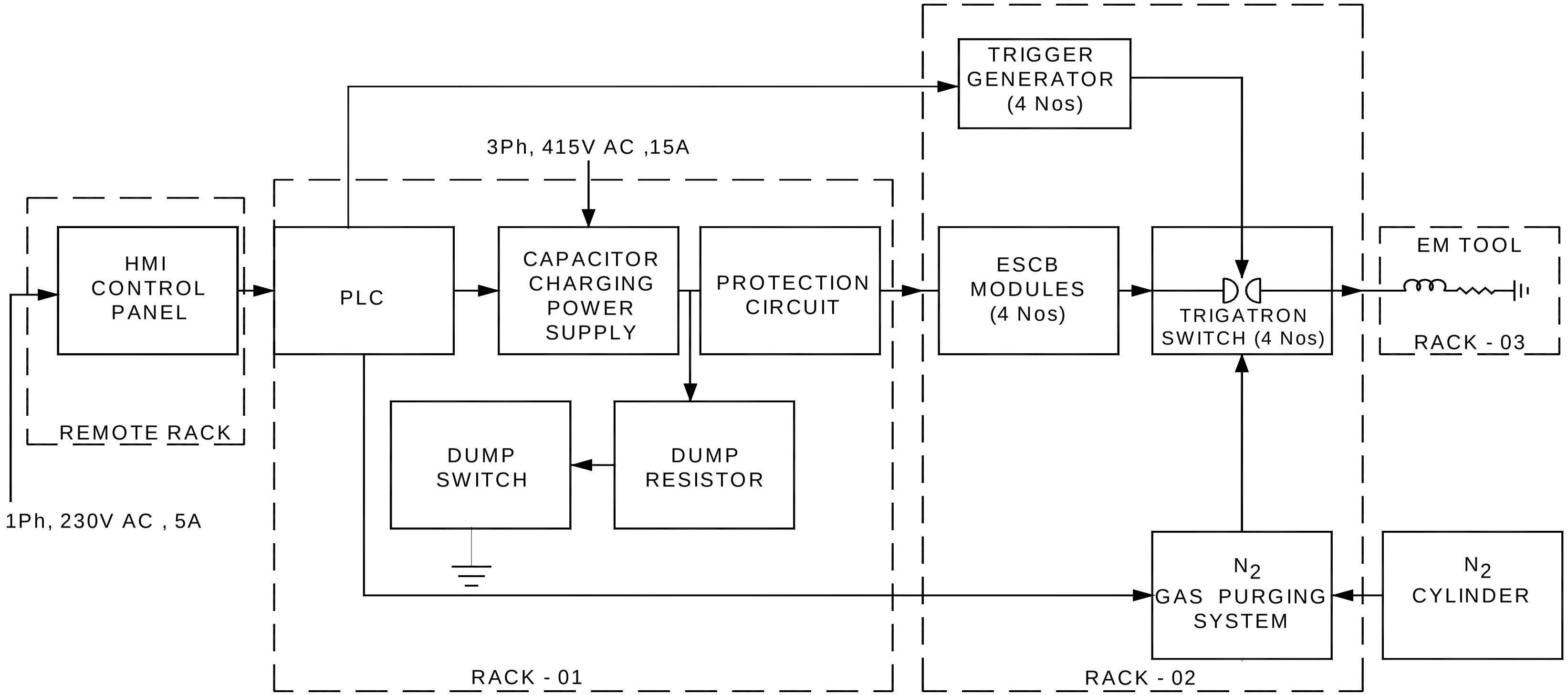


Fig. 2.1 Schematic block diagram of 40kJ, 20 kV EMM System

2.3.5 Single Trigger based Trigatron Spark gap Switch (TSGS)

a) Four TSGS with each switch mounted on a 20kV, 10 kJ capacitor bank module.

b) Operating range: Each TSGS has a trigger range of 75 % to 100% of the maximum operating voltage.

c) Design shot life: 10000 shots.

d) Coulomb rating: 2C for each TSGS.

e) Operating Environment: IOLAR Grade N_2 gas at 0.2 bar (gauge pressure).

f) Acoustic and EMI noise attenuation box-for enclosing TSGS

g) Trigger Voltage (OCV): ±20 kV

h) Trigger rise time: 100 ns with spark gap electrodes

i) Gas purging system using IOLAR grade N_2 gas

2.3.6 Trigger Generator

a) Four trigger pulses from a IGBT based trigger source

b) Command pulse: 15 V, 1 μsec to the gate of IGBT

c) Trigger capacitor charging supply:

Input: Primary: 230V, 50Hz

Supply output to IGBT with pulse transformer primary in series : 650Vdc voltage from a doubler circuit.

d) Trigger pulse transformer output: +/- 20kV, 100ns Trise, 400ns pulse width applied to trigger pin electrode of the spark gap switch.

2.3.7 Dump Switch

Used to dump the energy stored in capacitor bank through dump resistors.

Rating: 50kV, 60A. Vacuum contactor, Make: ITT, Jenning. USA.

2.3.8 EMM Tool (Load Coil)

Inductance: 0.5μH to 1.5μH,

Current : 300kA maximum

Voltage : 20kV maximum

2.3.9 Protections and safety

a) MCCB switch for incoming mains power supply protection against short circuit and soft start circuit to limit inrush current during bank charging and is located inside power supply rack.

b) Power supply overload trip.

c) Dead man's stick-for discharging capacitors before handling.

d) Acoustic and EMI noise attenuation box-for enclosing TSGS, mounted in capacitor rack.

e) Power line filter, to ensure power supply as electromagnetically compatible located in power supply rack.

f) HV danger board

g) Auto dump / charge prevention when rack is open

h) Grounding using copper bus bars.

i) Power supply protection circuit based on HV diodes and resistors shown in Appendix B4

j) Door switch is used for interlock with the power supply

2.3.10 General

The whole system is accommodated in three racks mounted on castor wheels to facilitate the movement of the racks.

a) Equipment Panel Size:

Power Supply & PLC Control rack (Rack-1): (800W. 800D, 2000H) in mm

Capacitor rack (Rack-2) : (1200W. 1200D, 2000H) in mm

EMM Tool rack (Rack-3) : (800W. 800D, 2000H) in mm

b) Operating Temperature: 10°C to 45°C

The Rack No. 1 houses a variable CCPS, vacuum contactor based dump switch and resistor tank and PLC controls. This rack also contains mains protective MCCB, power supply protection circuit and isolation transformer.

The Rack No. 2 houses the main Energy Storage Capacitors in four modules, each modules containing three 14μF, 20kV capacitors. It also contains four triggered spark gaps, one for each sub-bank module; multiple trigger generators that generate trigger pulse to close the spark gap switches.

The Rack.No.3 is an EMM tool rack that houses the EMM tool and coaxial current shunt (0.005 ohms) required for EMW/EMF operation. While measuring the current signal using digital oscilloscope; the output of the current shunt is fed through an isolation amplifier.

Lay out drawings of all three racks are shown in Appendix B, C and D.

2.3.11 PLC Controller

The control panel provides controls through a PLC based control system. It consists of Human Machine Interface (HMI), isolation amplifiers, transient suppressors and relays and a PLC controller (Model TWDLCAE40DRF, Schneider make). The control system is used to perform operation and monitoring of various parameters of the EMF unit. Since the EMF unit is a high voltage and high power system and is prone to generate high electrical surges in the event of a fault, it can result in catastrophic failure of the power supply and the control unit. Adequate protection measures have to be incorporated to prevent any failure of the components of the control system. To prevent component failures, two levels of protection schemes have been adopted in the system. The first level protection is done by providing fast acting surge suppressors to limit the electrical surges within safe operating limits of the components. For this purpose seven analog signals are connected through a transient suppressor module (SG770). This module has seven channels of transient suppressors, each of which can suppress a maximum surge voltage of 6kV of 8-20 us duration on either line with respect to earth besides taking a differential voltage of 30 volts. The second level of protection is provided by means of isolation amplifiers. The signals received from the transient suppressor module are fed through adjustable gain isolation amplifiers (ADAM 3014). This isolation amplifier provides a three port isolation of 3kV between input, output and power port. The gain of amplifier is selected through the DIP switches provided inside the amplifier to get the full scale span of 0-10VDC for an input signal of maximum value varying from millvolt to volts. Further, the operating panel is positioned in a safe distance from the EMF unit and proper care is taken to overcome EMI/EMC problems. All the signals from the isolation amplifiers are fed to the PLC analog input module. All the control and monitoring operations of the EMF system are performed using portable touch screen connected via Ethernet cable communicating on MODBUS/TCPIP protocol.

Broad specifications of the PLC based control system are as follows.

PLC: Model TWDLCAE40DRF, Schneider make

1. Digital input: 24 nos.
2. Digital output: 16 nos.
3. Ethernet port: 1 no.
4. RS485 port: 1 no.
5. Analog module with 8 channels analog input: Model TWDAM18HT, (Schneider make)

The PLC, remote HMI and PC are connected through 1:1 CAT-5 Ethernet cable plugged into a Ethernet switch. There are two HMI provided one for local operation and other for remote operation. A local control HMI is a 5.7" colour touch screen (Delta make). Local HMI communicate with the PLC on RS485. A 15 inch HMI (Model: XBTGT7340, Schneider make) with Ethernet port has been provided at operator station as man machine interface. It has one Ethernet port for either communications with PLC or for program download, and one RS 485 port to download program. The settings of different units are as follows.

1. PC Ethernet ID: 169.254.51.79
2. PLC Ethernet ID: 169.254.51.80
3. HMI Ethernet ID: 169.254.51.81

A simplified schematic diagram of PLC based control system is shown in Fig. 2.2.

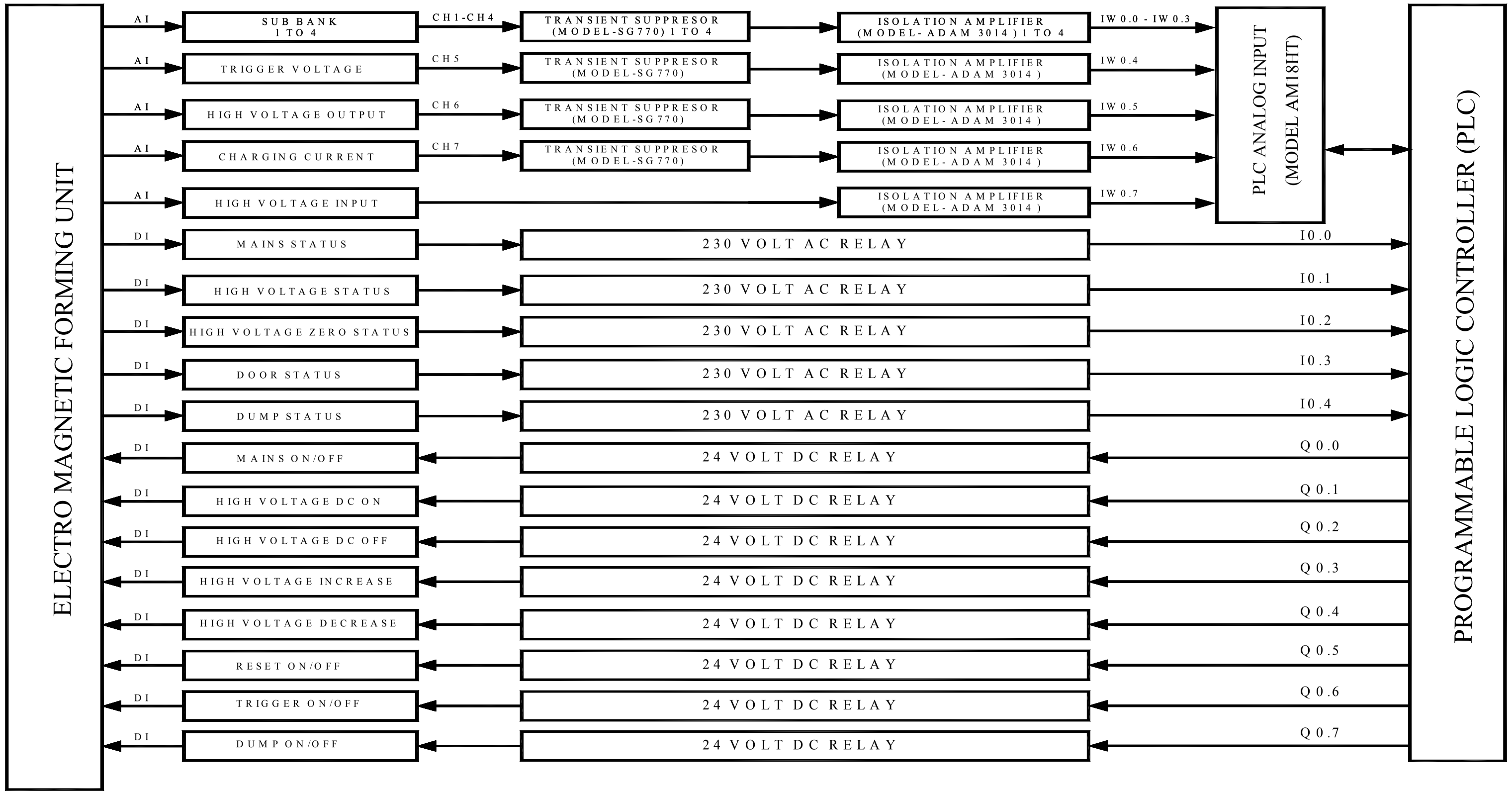


Fig. 2.2 Schematic Diagram of PLC based Control System

PLC Unit Operation

Switch On the MCCB (Rack-1)

1. Check the Emergency stop (Rack-1)
2. Check for the Mains, fault indicators (HMI Screen)
3. Check the welcome Screen on HMI
4. Then, Touch the screen to skip to the next screen till “Authentication Required” appear on the screen.
5. Then login using by the password (of level 1) provided by system administrator for entering the operating screen as shown below. *(Default password is 0)*
6. The operating screen is shown in fig. 2.3.

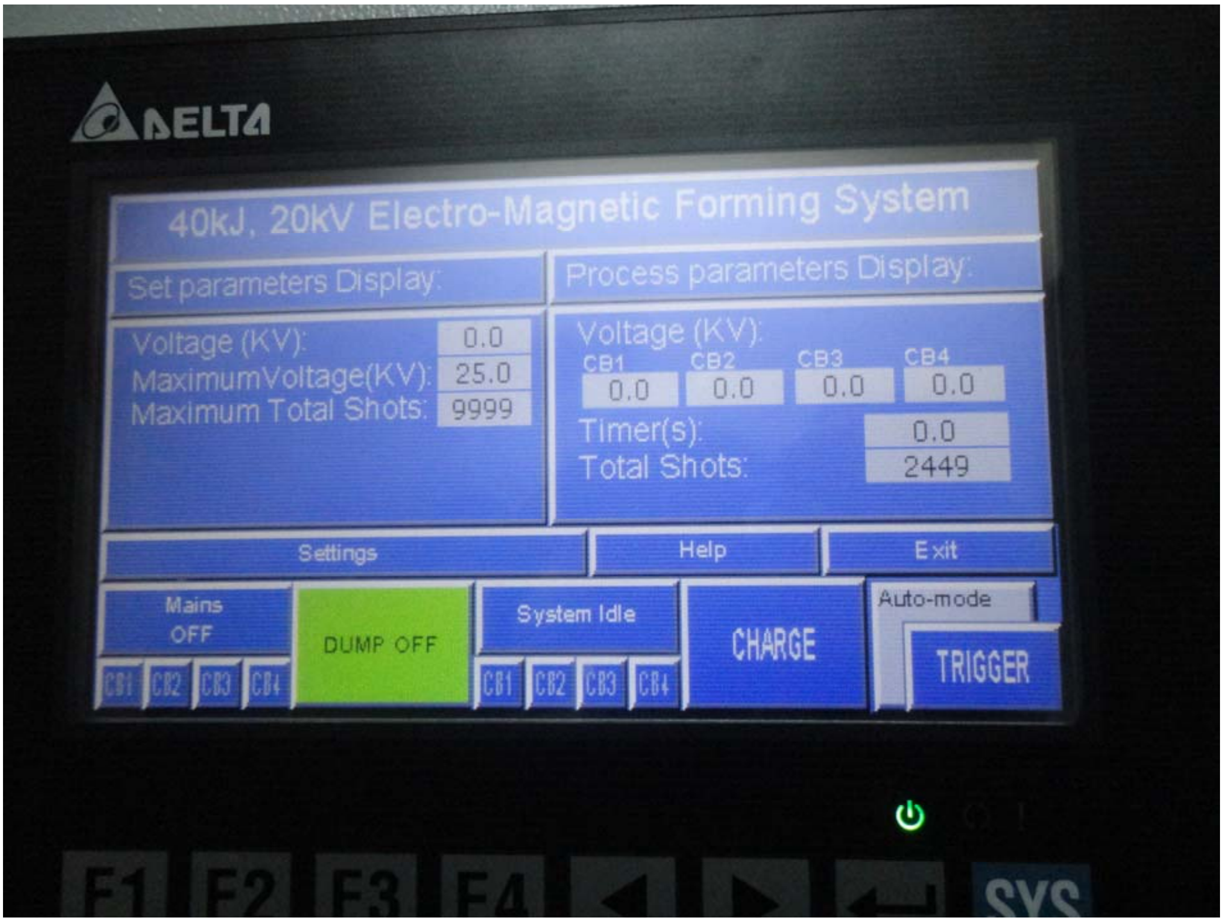
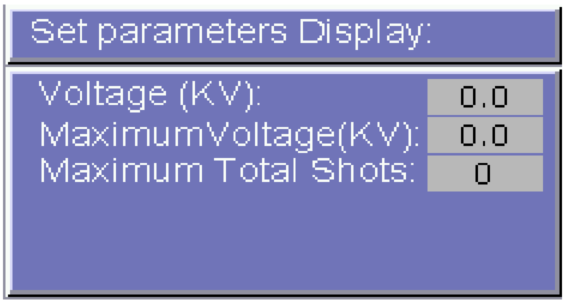
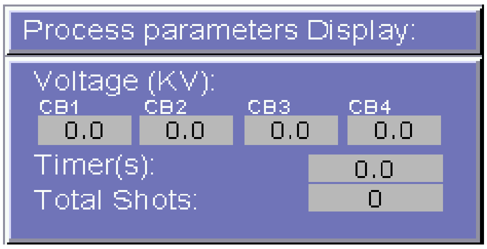


Fig 2.3: Screen is the main operational Screen of the HMI

- On the above Screen, we find seven controls (seven push buttons) and indicators (showing the set and process parameters)
- In the set parameters display block, the set voltage in kV is displayed as shown below. Maximum voltage (kV) displays the maximum settable voltage in kV. Maximum Total Shots indicator displays the set maximum number of cumulative shots.



- In the process parameters, process voltages of four capacitor bank modules, viz: CB1, CB2, CB3, CB4 are displayed as shown below. The timer (s) indicator gives the processed charging time in seconds. The total shots indicator display the cumulative number of shots taken upon the capacitor, its value is stored irrespective of the system is switched ON or OFF.



- Use the help button to find onscreen help
- Use Exit push button, to exit the operator screen.
- Use dump ON to discharge the capacitors through resistor bank.
- To set the set parameters, touch the settings push button on the screen. Then a password screen (of level 1) appears, to get authenticated to enter into set parameters sub-screen as shown below: *(Default password is 2).*

In the above sub-screen: Set voltage (kV) can be set by numerical buttons of the parameter. Trigger mode push button is used to set manual or auto-mode of triggering. In manual mode, after end of charge, the system awaits for operator interface to push the trigger button for triggering the charged capacitor bank. In auto mode, the system automatically triggers after the end of charge.

To exit the screen, press Exit push button.

- To set the capacitor parameters, touch the settings push button on the screen. Then a password screen (of level 2) appears, to get authenticated to enter into set capacitor parameters. *(Default password is 3)*
- To set the passwords in the password table, touch the password table push button on the screen. Then a password screen (of level 3) appears, to get authenticated to enter into password. *(Default password is 4)*

7. Press the mains ON push button on the screen of the HMI. Check the CB1, CB2, CB3, CB4 of mains ON indicator incase of any malfunction.
8. Set the voltage, mode, shots parameters as stated above on HMI.
9. Switch dump OFF.
10. Press the charge the charge push button to charge the capacitors.
11. After End of charge, if the Trigger button is in auto mode, the charged capacitor bank should get triggered automatically; or else, if the Trigger push button is in manual mode, push the trigger button after end of charge and to trigger the capacitor bank.
12. System idle, Charging, End of charge (and also of: CB1, CB2, CB3, CB4) are indicated by respective indicator.

CAUTION

IN CASE OF EMERGENCY OR ANY MALFUNCTION OF THE SYSTEM, USE EMERGENCY STOP BUTTON PROVIDED ON THE EXTERNAL FRONT PANEL OF THE SYSTEM.

2.4 Tool for Electro-Magnetic Manufacturing Technology

2.4.1 General description

1. System requirements for industrial mass production

The major factors, governing the economics of the Electromagnetic Manufacturing process with respect to industrial mass production are the component life time of pulse generator and coil, the repeatability of the process and the system's control algorithms. Further, there are some technical aspects, bearing strong relation to the EMM system size and thereby to the costs.

2. Component life time

Industrial mass production means batch sizes of 100,000 to several million parts per year. The life time of the costly components of the pulse generator is therefore specified by the batch size per year. It should be at least in the range of a two year production. Costly components are the coil and the capacitors, because of their purchase prize and even more because of the time which is essential for replacing those components. In a laboratory EMM system, replacing the coil may be a task of few minutes. However, this changes if the system is integrated into a production line. Hence, coil life time is required to be in the range of some million pulses.

In the past, EMM coils were commonly made of several windings of wire, embedded into an electrical insulator. This insulator was mainly made of plastics. The plastic insulator itself was surrounded by some metal or fiber reinforcement, enabling the coil to withstand the loads resulting from the magnetic pressure. This concept allows manufacturing multi-winding coils which can build up high magnetic pressure at relatively low discharge currents. This concept has one big pro but several contras.

The ratio of magnetic pressure to discharge current is high resulting in relatively small pulse generators and quite low electrical loads on all sensitive components (capacitors and switches). The biggest contra is the quite low coil life time. This is mainly due to the big discrepancy between Young's modulus of the electrical conductors and the insulating plastics which causes high strains in the conductors during the pulse. Young's modulus of copper is 1,15,000 MPa, but that of fiber reinforced plastics is only round about 20,000 MPa. The factor of 5.75 between the two material's elastic properties means, that under elastic conditions the plastic will reach the same stress as the copper at 5.75 times the strain. Hence, there is no real reinforcement effect of the insulator. The pressure acting on the coil in radial direction will cause an expansion of the coil. Magnetic pressure is also present in the axial direction. This pressure component causes a compression of the coil in axial direction. The magnetic loading causes displacements inside the copper-insulation composite, resulting in fast ongoing micro fractures in the insulation. When the isolation is weakened by multiple cracks normally a short cut between the coil windings or cracks in the electrical conductor will happen. Building self reinforcing coils can help overcoming this problem. However, adding many windings to such a coil is more complex. Thus, self reinforcing coils normally are characterized by only some few windings, usually in the range between 1 and 5. As the number of windings is directly coupled to the magnetic pressure, these self reinforcing coils require elevated discharge currents. This disadvantage of the self reinforcing coils is more than balanced by their high life time, which is often 2 million pulses or even more.

Elevated discharge currents will lead to increased wear of cables, capacitors and switches. However, modern cables, capacitors and switches are capable to withstand pulsed electrical currents in the range of 10 to 300 kA. Here, parallel use of these components helps to cope with currents in the range of 100 kA to 1000 kA. Proper component design leads to cable and capacitor life time of approx. 10,000 shots even with respect to pulse generators of the 100 kJ class.

3. Matching system settings to the process requirements

As the price of the EMF system significantly governs the economics of the process, choosing the proper system configuration is mandatory. The important parameters are described as

1. Cross-sectional dimensions of the tube or profile
2. Work-piece material properties
3. Magnetic pressure essential to accomplish the forming, cutting or joining operation
4. Length of the pressure loaded area

The combination of these four aspects defines the characteristics of the system:

1. Coil and field shaper

2. Discharge current

3. Discharge frequency

4. Choosing the operating frequency

For crimping and forming operations the operating frequency is directly governed by the work-piece's wall thickness and its electrical conductivity. This correlation is caused by two mechanisms, based on the skin effect and the correlation between magnetic pressure build up and the magnetic flux density distribution at the inner and outer circumferential face of the tubular work-piece. The skin effect is the characteristic of alternating currents to locate in a thin layer near the work-piece surface. The thickness 'δ' of this skin depth layer is given by Eq. (2.4).The variation of skin depth vs electrical resistivity of most common materials at various operating frequencies is given in Fig 2.4 [7].

The dependency between the magnetic pressure and the difference of the magnetic flux inside and outside the tubular work-piece is given by the following equation:

$$P_{mag} = (B^2_{out} - B^2_{in})/2\mu_0 \tag{2.7}$$

In case of a tube compression, Eq. (2.7) computes for the highest magnetic pressure, if there is no magnetic flux density at the tube's inner wall. This is roughly estimated true, when the skin depth is smaller than the tube's wall thickness. A skin depth exceeding the wall thickness of the work-piece, will cause significant losses in magnetic pressure.

A rule of thumb for estimating the operating frequency for sufficient build up of magnetic pressure is therefore given by Eq. (2.4). If the frequency is increased above the value computed by Eq. (2.4), no further significant pressure build up will be possible. However, an increase in operating frequency boosts the velocity of the work-piece and therewith the strain rates. The strain rate influences the yield stress of the tube material. Increasing the operating frequency also enlarges the tube accelerations and therewith the inertial forces. Hence, even if the correlation between strain rate and initial yield strength is negligible (i.e. for many aluminum alloys), a higher magnetic pressure will be essential when the forming result should be constant, but the operating frequency is increased

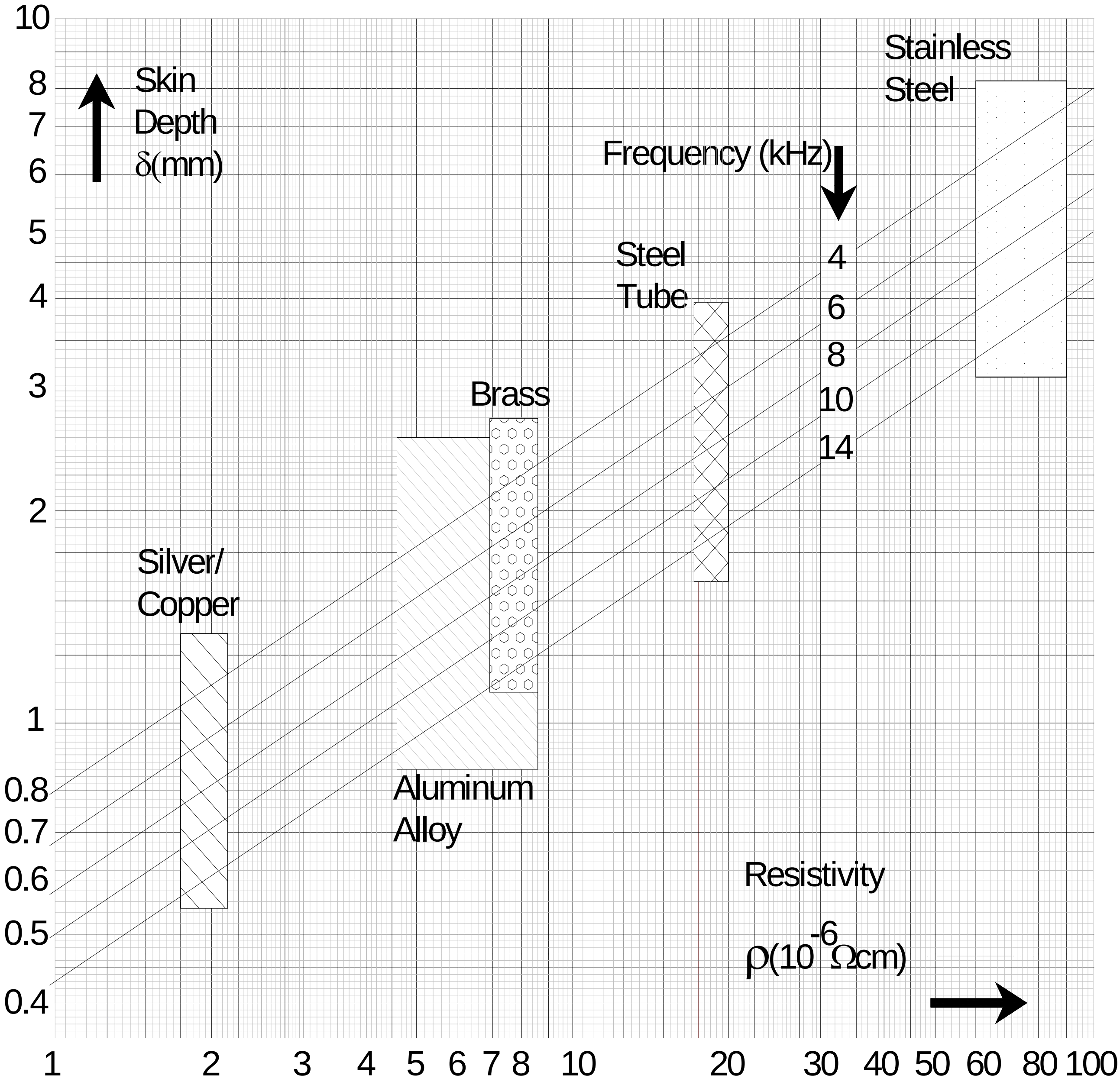


Fig. 2.4 Chart for skin depth vs electrical resistivity of most common materials at various operating frequencies. [7]

5. Coil basics

The inductance of a long coil (When length significantly bigger than its diameter) is approximately given by

$$L= 2\pi\ r\ \mu N^2/\ l \tag{2.8}$$

Where L denotes the inductance, μ the magnetic permeability, *r* the coil's radius, N the number of coil windings and *l* its length [8]. The operating frequency is given by Eq. (2.5). Normally the self inductance of the pulse generator is far below that of the coil. Eq. (2.8) shows, that an increase in coil diameter and the number of coil windings boosts the coil's inductance. However, according to Eq. (2.5) an increase in inductance decreases the ringing frequency. On the other hand, the number of coil windings is directly related to the magnetic pressure. Hence, choosing the appropriate number of coil turns is some kind of optimization problem. However, the bigger the coil diameter, the less windings should be used, because of the consequent increase in inductance.

The tangential and radial stresses are not only stresses encountered in a pulsed coil, the radial component of the field gives rise to axial compressive stress. The radial component of the field is strongest near the ends of the coil and decreases to zero at the mid plane, and the self –force is therefore greatest on the end turns

6. Flux Concentrator

Form of the pulse coil which combines aspects of both uniform-current density and disk construction. It is actually a current transformer and relies on a current discharge through a uniform-wound multi-turn primary to induce a current in a single turn secondary enclosing the bore. This device has provision in allowing special shaping of the single-turn, low voltage secondary, and in general, it restricts the high voltages to the uniform –wound primary, where the stresses can be minimized. Good coupling between the primary and the secondary is achieved by embedding the primary in the outer surfaces of the single-turn secondary.

7. Field shaper

The field shaper focuses the magnetic pressure on the area to be deformed. It is not a must, but however, it is beneficial because of several reasons. In case of changes in work piece diameter, only the field shaper and not the coil must be replaced. The field shaper locates the pressure on the work-piece. Hence, the coil is loaded with minor pressure than the work-piece, which results in improved coil life time. When a field shaper is inserted into a compression coil; the coil induces surface currents in the outer circumferential face. These currents run via at least one slot of the field shaper to the field shaper bore. The bore length is usually smaller than the field shaper length. Hence, the current density is increased. This causes a local elevated magnetic pressure. The magnetic stress related to field of 50T is 10kBar (1GPa), close to the yield point of the strongest alloy. It is possible to make massive coils with distributed stress that will work in the range of 50-100T but the danger of destruction is sharply increased. The design principles for nondestructive pulsed coils are closely related to those for stationery fields. Pulse field coils are heated adiabatically during the current pulse

8. Coil Health Monitoring

To prevent the damage caused by a coil implosion, it is a good practice to monitor the inductance and resistance of the coil and check every magnetic field record (i.e., the sensitive dB/dt signal) for the onset of irregularities which may indicate impending failure. Another method is to use a microphone to monitor the noise made by the coil during the pulse, and to compare this by computer to a prerecorded standard noise pulse. In the disk type coil the material of the turn acts on both the inertial mass and retaining bound unlike in helical coil where additional redial reinforce is provided by extra radial binding.

9. Thermal Aspects

When high discharge current flows through the coil, it is subjected to mechanical and thermal stresses. If the conductor area is insufficient to carry the discharge current (I), the temperature (T) of the conductor may increase to a dangerously high level as a result of which insulators in the vicinity of the conductor are severely thermally stressed. The contacts experience temperature stresses proportional to I^2Rtp. The resistance (R) depends on the contact pressure and surface condition. The thermal stresses depend on the r.m.s. value of the discharge current and the time period (tp) for which this current is carried by the coil. During discharge, it is assumed that all the heat is absorbed by the conductor; there is no sufficient time for radiation. The temperature rise is calculated by using the formula:

$$T = m\,(I/A)^2\,(1+\alpha) \qquad (2.9)$$

T= temperature rise/second in degree C

m= Mass of conductor in kg

I= r.m.s.current

A= active area of cross section of conductor $(mm)^2$

α= temperature coefficient of conductor resist at 20˚C

During discharge, at a temperature of about 160°C aluminum becomes soft and loses its mechanical strength. This sets a limit on the permissible temperature rise which in turn depends on the cumulative shots.

10. Control algorithms

Today, economical mass production requires the application of online quality insurance systems. Often, these systems save relevant process data in a common database which provides possibility to retrieve information on any process, the manufactured part had undergone. The result of a process is mainly related to the magnetic pressure applied to the specimen. So if there are only minor deviations of the material parameters within a work-piece batch, it is essential to keep the current and therewith the magnetic pressure constant. For this, on the one hand a constant charging voltage of the capacitors is essential, which is a question of the charging device's quality. On the other hand, parallel firing of all high current switches of the pulse generator within some nanoseconds is mandatory. Non parallel firing of the switches will result in deviations of the first current amplitude and the discharge frequency. Additionally, a 100% control of the discharge current history of every pulse helps providing useful data for the quality insurance system. By monitoring the current amplitude and the frequency, the integrity of the machine is verified. In many cases these two characteristics can be even used to identify whether a work-piece is inserted in the coil bore or not. Moreover, an appropriate pulse generator control algorithm can ensure the process stability by increasing the charging voltage, i.e. when one capacitor fails at the end of its life time. However, in case of a capacitor failure, the discharge frequency will also be changed. Hence, an automatic disconnection of the failed capacitor and an increase of the charging voltage for the working capacitors to reach the same discharge current as before the fail is not the appropriate solution. The better way is the use of a process window, which correlates discharge current and frequency to the result of the process. Control algorithms for mass production EMM systems should additionally provide the possibility for remote software maintenance and remote hardware diagnosis to minimize machine down times.

In mass production, EMM is in a strong competition to conventional forming and joining processes. Hence, the technological benefits of EMF will only be taken in account, if there are at least non economical benefits. However, in most of the cases, this new technique will only be adopted in mass production when technical and economical benefits are given.

For gaining economical benefits, EMF system life time must be in the range of a two year component production. This can be accomplished by high quality switches, capacitors and cables and strong coils.

2.4.2. Design and development of a Solenoid coil and field shaper for a sample job

A Electromagnetic Manufacturing Tool has been designed and developed for joining a job sample consisting of Copper tube to Soft Iron Disc having the following specifications:

Table 3: Job Specifications

Tube Material	Copper
Yield Strength	275MPa
Tensile Strength	310MPa
Hardness number	55
Conductivity (20˚C)	101%IACS
Melting point	1083˚C
Active length of Job-Piece	8.5 mm
I.D	42 mm
O.D	48 mm
Thickness	3.0 mm

The process requires joining of above specified tube over soft Iron disc

2. Dynamic Pressure

Yield stress required to just form (Ys) = (Yield strength of Copper X Thickness) / O.D

= 275MPa X 3.0 / 48 = 17 MPa

The pressure required to form/join Copper tube to Soft iron rotor is considered to be 10 times more than pressure required to just yield. This figure is arrived at, based on experience that takes into account the leakage in the field, work hardening due to high strain rate forming etc [9].

Hence Pressure needed to be generated Pg =10 x 17 = 170 MPa

3. Magnetic Field

The field necessary to generate 170MPa is given by, $P = B^2/2\mu_0$, assuming that no field penetrates out of surface. The field required to be generated B = 21 T.

4. Geometry of the Coil and Field Shaper

4.1 Magnetizing force required to generate ~21 T is given by $H = B/\mu_0$, H = 16.5 MAT/m at the interface of job and field shaper.

4.2. Length of the field shaped is considered 25% more the active length of the job to be formed i.e.10 mm. To generate 16.5MAT/m, current required to flow in the field shaper would be $16.5 \times 10^6 \times 0.01$ =165 kA. Field shaper and job interface is the highly stressed part of the EMM tool. Hard drawn copper is chosen for field shaper fabrication

4.3. Considering 50% coupling between coil and the field shaper (practically fair in air), Magnetizing force to be generated by Coil is 16.5 / 0.5 = 33 MAT/m,

4.4. It was decided to design self reinforced disc type coil which overcomes the problems of yielding of insulation (reinforcement) under elevated pressure. As, adding many windings to the coil, increase its complexity, it was decided to go for maximum of five turns. (Normally, self reinforcing coils are characterized by only some few windings, in the range between 1 and 5 turns.) As the number of windings is directly coupled to the magnetic pressure, these self reinforcing coils require elevated discharge currents which are considered while decided the thickness of the discs.

4.5. The Coil turns are in the form of heavy duty AA2024 aluminum discs (8 mm) isolated by FRP discs (1.7 mm) laminated with Mylar (3mil) insulation both sides. Inter turn connectivity is established by hard drawn copper sectors. All discs are fastened axially by M16, SS304 (non magnetic) studs. Isolation between coil turns and SS studs is achieved by 1.2 mm thick Delrin cylinder. Studs are further insulated by 3 mil thick Kapton tape. Field shaper and coil turns are also isolated by 1.2 mm thick Delrin cylinder. All FRP discs are extended 5mm radially more than the Aluminum disc to take care the surface flash over. Due care is taken to mitigate surface flasher over between inter-turns at inner bore of the coil

4.6. Inter-turn contact is established by hard drawn copper sectors which forms the Cu-Al contact surface under high pressure. The copper sectors reduce the drop at elevated current and in turn reduced the junction heat dissipation as compared to Al sectors. Table 4 gives the comparison of properties of copper and aluminum used in circuit breaker contacts where high electric, mechanical and thermal stress is encountered.

Table 4: Comparison of properties of copper and aluminum

Conductivity for equal areas copper	Copper	Aluminum
Electrical	1.0	0.62
Thermal	1.0	0.56
Tensile strength (Hard -drawn)	1.0	0.40
Hardness (Hard -drawn)	1.0	0.44
Modulus of elasticity	1.0	0.55
Coefficient of thermal expansion	1.0	1.39
Melting point	1.0	0.61

5. Current Requirement

5.1. Axial filling factor of the winding 48(conductor length)/58(total length) is 0.82. A

5.2. Axial field shaping factor 58(length of coil)/10(length of field shaper at ID) is 5.8

5.3. OD to ID ratio of the shaper 90/49 is 1.83. ID of field shaper decided on the bases of OD of the Copper tube to be formed and the play for the insulation. The air gap between field shaper and the job to be formed should be as minimum as possible to have better coupling efficiency.

5.4. Active total Number of turns: 5 x (1- 45/360) = 4.375; as 45˚ is the angle subtend by copper sector that part won't contribute to the effective turns.

5.5. Magnetizing force needed to generate by coil (16.5/0.5)/(5.8 x 0.82) is 6.9MAT/m

The Current I necessary to generate 6.9MAT/m magnetizing force is given by

$I = (6.9 \times 10^{6} \times 58X10^{-3}) / 4.375 = 92$ kA; where length of coil l = 58 mm and number of turns of coil N=4.375

6. Inductance of The Coil

Inductance $L = 25.4*10^{-3}*d^{2}*N^{2}/(18*d+40*la)$ uH Where d is the average effective diameter of coil in meter , la is the active length of the coil in meter and N is the total number of the turns. In present case N=4.375, la =58 mm d = 90 mm (Without Field Shaper). L = 1.6µH is the inductance of the five turn coil which is definitely come down with field shaper. Measured inductance and resistance of the coil with field shaper at 10kHz are 0.944µH and 12.21mΩ respectively [7].

7. Frequency of Operation

A 224µF, 20kV, EMM, total system inductance includes the inductances of: capacitor bank, trigatron switches, coaxial structure and cables besides coil inductance. Inductance offered by total 16 capacitors is about (~128/16) 8nH. The inductance of all four switches in parallel offers (~40/4) 10nH. The discharge coaxial cable 2297 (50kV, 50A DC) has the inductance of 126nH/m length, eight cables in parallel each of 5.0m long offers ~157nH. The total inductance of the bank works out to be 175nH. Total inductance of the system including coil is

~1.0μH.(considering 10% higher inductance). The ringing frequency is given by f = [2π (LC) ^{½}]^{1} = 10 kHz neglecting the damping resistance of system.

8. System Operating Voltage

To get current I = 92kA the system has to be operated at voltage V = 14.3kV. The operating voltage is given by V = K (d) x I/(L/C), where K(d)=0.8, is a function of damping factor and close to 0.8 for good reversal system.

9 Skin Depth

For effective and efficient forming skin depth should be order of thickness.

Skin depth $\delta = (\pi \sigma f \mu)^{-1/2}$ with usual notations,
For δ = 3 mm (for Cu), operating frequency is ~ 500Hz;

For δ = 1mm(Cu), operating frequency ~ 4.5kHz and for 10kHz operating frequency entire field generated would confined on the job and diffused out field is negligible. Due to higher operating frequency, current required to form could be greater than 92kA which can be met by operating the system at higher operating voltage which can be determined by the experiments.

10. Force Acting On the Coil

Force generated by the field shaper on job is equal to the reactionary force on the field shaper which is equal to the product of the field shaper active area and the pressure, i.e.,

Force on job = Force on field Shaper = Pressure x Area

$$= 170 \times 10^{6} \times 50 \times 10 \times 10^{-6} \times \pi$$

$$= 267\text{kN} = 27231\text{kgf} \approx 27.23 \text{ ton (peak)}$$

and half sine wave period is 50μsec.

11. Diffusion Time Constant

The diffusion time constant of the tube is given by, $\Gamma = \sigma\ \mu r_0 d_0/2$ where r_0 is outer radius and d_0 thickness of the tube, σ is the conductivity of the tube material. For the given job, Γ works out to be 2.62msec. For best results rise time of the pulse should be less or equal to the diffusion time besides satisfying skin depth criteria. In present case both skin depth criteria and diffusion time criteria are satisfied.

12. Job Fixture

Asymmetrical positioning of the job inside high pulse magnetic field ejects the job from high field zone and energy is not utilized effectively in forming/welding of the job piece. For efficient forming/welding job piece (copper tube and soft iron rotor in present case) has to be held in its proper high field zone till whole magnetic pulse dies out.

The fixture consists of 12 mm thick SS 304 plate, 90mm wide, 250mm Ø, fitted on left end of the coil with the help of two axially binding bolts where as collar of the field shaper exists at right side of the coil. A Delrin block is fitted at field shaper recess whose function is to stop the movement of tube (job piece) without affecting the field pattern. A 16mm Ø, SS guide is provided at the centre of the coil and was fixed to the 12mm thick SS plate by threads and nut. The function of SS guide is to maintain concentricity of soft iron rotor and copper tube. While taking shot after inserting rotor and copper tube, the job was held firmly in its position by washer and lock nut.

2.4.3. Design and development of a Flat coil for EMF/EMW

The procedure for lap welding of two Al strips of 5cm x7 cm x3 mm thick flat sheets is described here [10].

The required pressure for welding Al-Al (3 mm thick flat sheets) is obtained experimentally. It is taken that 50% of capacitor bank energy is delivered to work-coil. 30-35% of this energy is coupled to job-piece in case of flat sheet welding. Part of this coupled energy to the job-piece is used in deformation of job-piece and remaining part is utilized as a kinetic energy of job-piece.

Bank Energy ≈ Coil Energy = KE of Job-piece + Deformation Energy

$$\{F\} \text{ x A} = [M]\frac{d^2}{dt^2}\{u\} \text{ x A} + [K]\{u\} \text{ x A} \tag{2.10}$$

Where K- Stiffness, u - velocity, M - mass and A is area [11].

From the ESCB ~6kJ is imparted to job-piece. From experimental data it is known that for welding of 3 mm Al samples, 350 m/s of velocity is required. It amounts to ~1.5 kJ of KE. Rest ~4.5 kJ of energy is utilized in plastic deformation and bonding.

To attain this velocity of 350 m/s, pressure required for welding of flat sheets of Al-Al (both 3 mm thick) is 300MPa.

The magnetic field to generate 300MPa is derived as follows; Pressure P generated on the job piece is given by equation (2.7).

It is found that for the maximization of the impact force, the frequency of current should be 20 kHz. For 20 kHz frequency, for 3 mm thick job-piece magnetic field B_o is found to be 30% of B_i. From equation (2.9) for 300MPa pressure B_i = 28.77 T and B_o= 8.60 T. Here we have neglected the contribution of magnetic field by induced currents generated in the conducting Al job-piece.

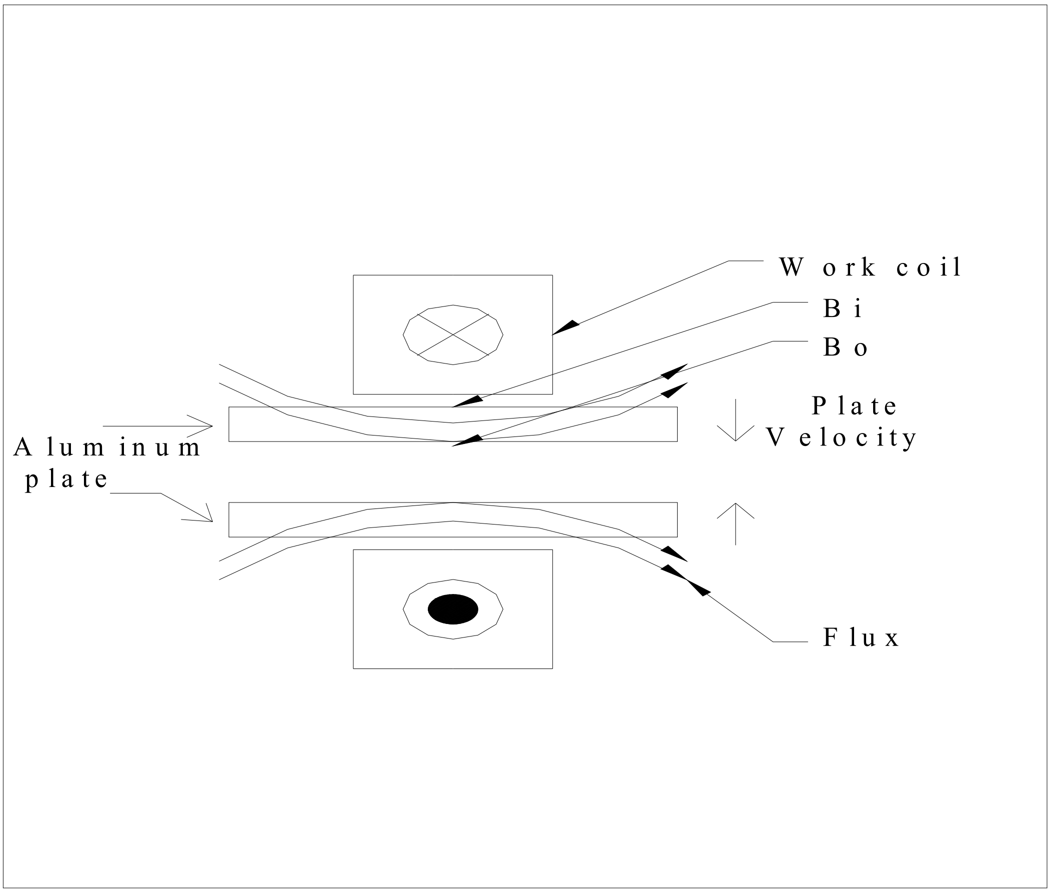


Fig. 2.5 Coil current and magnetic field

The current required in long conductor to generate required magnetic field B_i is given by

$$B_i = \mu_0 I/2\pi d \qquad (2.11)$$

I is required value of current in the coil.

For Bi = 28.77T and d= 1.5 mm, I= 210 kA.

Here d is separation between coil and job-piece. In principle it should be minimum possible for best coupling of magnetic flux between the coil and the job-piece. Due to insulation requirement between the coil and the job-piece, it is limited to a value of 1.5mm.

The frequency of EM system (Concept of skin depth) is explained here. Current in a conductor does not flow uniformly throughout its cross-section. It flows in the skin depth. The frequency is selected such that the skin depth in the job piece is smaller than the job thickness. Under this condition, an appreciable amount of magnetic field is confined within the job-piece. Skin depth is given by Eq. (2.4).

Taking skin depth in Al = 0.6 mm, frequency (f) of the system comes out to be 18 kHz. Frequency of under damped RLC circuit is given by Eq. (2.5). Here resistance of the system is neglected. Here f = 18 kHz, C= 220 μF and value of total inductance of circuit L= 350 nH. Out of 350 nH, 300 nH is of the capacitor banks and connecting bus-bars. Hence single turn welding coil can have a maximum inductance of 50 nH.

Maximum cross section area of coil for permissible current density (J) is estimated as follows: For pulsed operation, the allowed current density (J) through a copper conductor is 2 kA/ mm^2 without overheating of conductors or mechanical damage. Hence the required cross-section area of the coil conductor is

$$A = \frac{I_{max}}{J} \tag{2.12}$$

For a peak current of 210 kA, we should have minimum 52 mm^2 cross-section area of the coil. Design of two coil geometries (Fig. 2.6) are provided to study the effect of coil geometry on EM welding of sheets. Cross- section area is taken more than required to have some safety margin. The tapered coil is chosen to increase the current density at lower end.

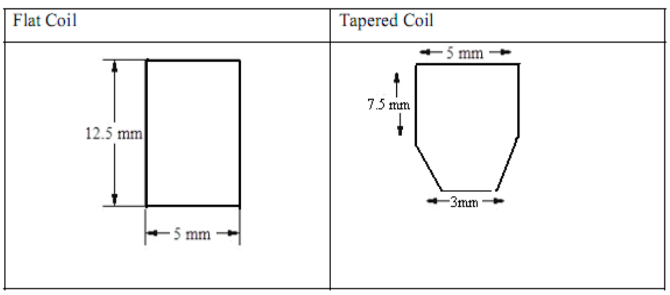


Fig.2.6 Flat rectangular and tapered cross-section of the coil

3. System Testing and Commissioning

3.1 Sub-System Testing

3.1.1 Capacitor Bank (Rack-2)

Caution: During the measurement of sub-bank capacitances, as a part of preventive maintenance exercise or fault diagnosis in the case of sub-bank failure, please ensure that the capacitors are fully discharged and the dump switch is in 'OFF' position. In addition 'dead man's stick' should be put on the sub-bank terminals before undertaking it for the maintenance.

(a) Before assembly of the capacitor bank, each individual capacitor in the capacitor bank assembly must comply with the requirements of the following tests:

i) 50 shots charge/discharge test at rated voltage, current and % reversal.

ii) Measurement of capacitance (C) and Tan 'δ' before and after charge/discharge test and ensuring that the % change in these values after the charge/discharge test are within the stipulated values of ± 5% .

iii) One minute high voltage (100% of rating) withstand test.

iv) Inductance measurement on capacitors.

(b) Owing to the assembly and wiring of energy storage capacitors sub-bank (as given in Appendix- A3 and C1, the possibility of measuring only the sub-bank capacitances exists. Ensure that each sub-bank capacitance (4 x individual capacitance) is within ± 5% tolerance. Portable, digital R, L, C meter at 1kHz, is used for the measurement.

Sub-bank's isolation from the capacitor rack body is ensured by measuring the resistance using millimeter between terminals connected to the capacitor body and the rack. Meter should indicate open circuit.

(c) After assembly of the spark gap switches and mounting on the capacitor bank modules, each sparkgap switch is tested for the self breakdown voltage using a Megger of rating 0- 30kV, 0-5ma. By testing, it is ensured that each sparkgap switch should have a breakdown voltage of 22kV ± 0.5kV.

(d) Ensure that the capacitor bank rack is wired as per the wiring diagrams given in Appendix A3 and A4.

(e) 'Door open' indication on HMI panel will appear when the Rack -1 and 2 doors are open. This interlock will disable charging of the power supply.

3.1.2 High Voltage Power Supply and PLC Controls (Rack-1)

(a) Ensure that the components layout in the power supply racks and the circuit connections have been made as per the drawings given in Appendix A4 and B1.

(b) Ensure that the power supply, dump resistor and Protection circuit have been independently tested for their specifications before their assembly in the power supply rack.

(c) Operation of the vacuum contactor (Dump switch) and its main and auxiliary contacts change over has to be ascertained before connecting in the circuit. Please note that when not energized, or in the case of power failure, the main contacts, connected to the Dump resistor stack of the capacitor bank, are in normally closed condition, thereby connecting the capacitors to the system ground. This ensures a fail safe operation of the capacitor bank.

(d) Prior to testing with the capacitor bank, the High voltage power supply (PS) is independently tested with the energy storage capacitor bank on an external capacitor of similar rating using charging cables (RG-8/U), but in conjunction with the PLC Control Panel and Dump unit. This will ensure that the control panel is assembled and wired as per its relevant layout and wiring diagrams. 0-25kV DC Meter with high voltage probe (P6015A Tektronix make), is employed for making this measurements up to 20 kV dc. PLC with HMI panel is employed during the independent testing of the Power supply. All operations of switch ON and OFF should be followed as per PLC control system.

Note: Ensure that the trigger pulse transformer and trigger capacitor charging cables and energy storage capacitor charging cables are disconnected before the measurements. If any of the above six observations are not met as mentioned above, do not proceed ahead with the testing. Switch OFF the mains using MCCB and resort to corrective measures by tracing the fault with the circuit/wiring diagram of the respective panels and their interfaces.

Dump switch is then put ON, once the above steps are successfully executed. This step is a must, before the high voltage charge touch screen button on HMI is put ON. This is an interlock to ensure the intended charging of the bank or for making the high voltage power supply ON.

'Charge' touch screen button is pressed ON. The charge button indicates 'High voltage ON' The PLC operation is described in detail in Chapter 2.3.1.

Caution: All the power terminals and high current terminals should be tightened adequately before commencing with the test. The metal body of capacitor ground terminal should be connected to mains ground busbar using copper strip (50mm wide and 3mm thick). All the rack should be connected to the mains ground busbar using copper strip.

(e) Short Circuit Tests of power supply: This test loads the power supply and its associated components to their full peak power values (as required while charging the capacitor bank), for a time period of only eight seconds. Short circuit tests should be conducted at the manufacturer's premises as per power supply specification given in Annexure-1.

3.2 Complete System Testing and Commissioning

Ensure that all the sub-systems have been tested in accordance with their aforesaid relevant test instructions and they are interfaced with each other before starting the test and commissioning trials on the system. A strong coil (5 to 15μH) preferably with a dummy job piece should be used as load. The following steps are followed.

Note: It is important to test individual sub banks before connecting all the banks with the load in steps of 1kV in the range of 15 to 20kV without trigger and by using the dump switch. For testing of each sub bank the strip line connections to the remaining banks and also the charging cables should be disconnected. This test is to check whether the TSGs withstand the system's maximum operating voltage. Any breakdown of the TSG during the above tests will call for a repeat of the test and possibly switching off the system for opening of the capacitor bank rack and then the TSG switch enclosure and setting of gap spacing. Checking the gap for specified value of 8.5mm and cleaning the spark gap electrodes using dry tissue paper.

(i) Connect the system power cord to 3 Phase, 415V, 15A, 50Hz Mains power supply. Ensure that Mains ON/OFF switch (MCCB), is in OFF position before the mains power supply is put ON.

(ii) At the control panel, switch on the mains ON/OFF using touch screen button on HMI.

(iii) Charge the individual banks to about 3kV and check for operation of the trigger and dump switch. A cracked noise of auxiliary spark gap and main spark gap triggering is heard. Only after ensuring this step is smooth operated, the next steps should be taken up.

(iv) The complete operation of one module will be tested by charging the module capacitor bank to its ratings in steps of 1kV in the range of 15 to 20kV with trigger and by using the dump switch. Observe the Current Shunt/ Rogowski coil output at the oscilloscope and determine the load current from Current Shunt/ Rogowski coil sensitivity and record current waveform on oscilloscope. Knowing the circuit impedance and charging voltage (range of 15kV-20kV), peak load current can be calculated and compared with the peak current recorded on the oscilloscope. The values of the peak current thus observed should be well within ±5% of each other.

(v) The above step should be done for each sub bank. After completing testing of all the four individual sub bank modules, and after ensuring satisfactory operation of each modular sub bank, the integrated testing of the sub banks should commence.

(vi) Two sub banks can be integrated and tested according to procedures mentioned above. It has to be ensured that stripline connections and power supply cable connections are completed before simultaneous testing of multiple sub banks.

(vii) The above integrated testing should be done in steps of two, three and four sub banks. Verification of the peak current ratings in steps of 1kV in the range of 15kV to 20kV in that order, clears the system operations and qualifies the system commissioning. System can be switched off after reducing the system voltage to zero.

(viii) Each individual capacitor sub-bank module is tested by applying a DC charging voltage and discharging through a load coil (2.4µH) in steps between 14 kV to 20 kV. The testing should be done using the CCPS power supply, PLC control unit and monitoring the discharge current waveform on an oscilloscope using current shunt 0.00054 Ω (T& M Research make). Sample discharge current waveforms of single module (CB-1) and two modules (CB-2, CB-3) sub banks charged to 15kV are shown in figure 3.1 and 3.2 respectively.

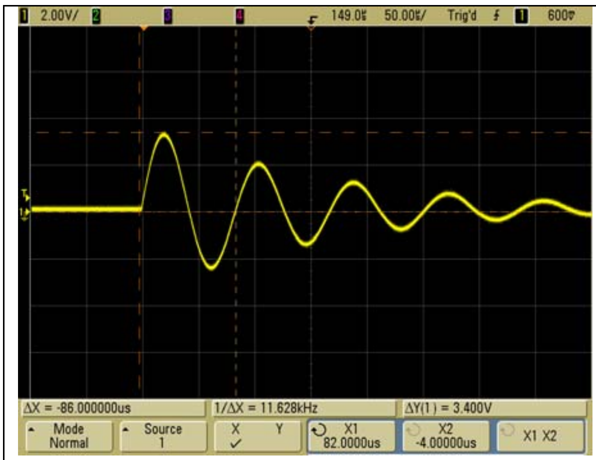


Fig. 3.1 CB-1: Peak current: 61.2 kA, Frequency: 11.6kHz without field shaper and job

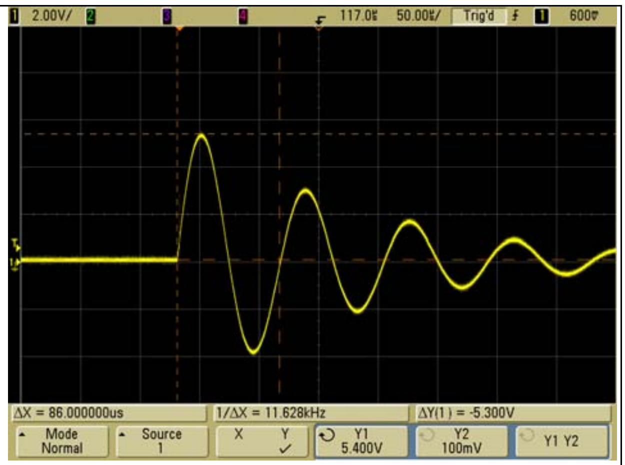


Fig. 3.2 CB-2 & CB-3, Peak current: 97kA, Frequency: 11.6 kHz with field shaper and job (Al tube: 51 OD, 45 ID)

After successful testing of individual sub banks and two sub banks together, Testing of three & four sub-banks are taken up. Discharge current waveforms of three (CB-1, CB-2, CB-3) and four (CB-1, CB-2, CB-3 & CB-4) sub bank are shown in figure 3.3 and 3.4 respectively.

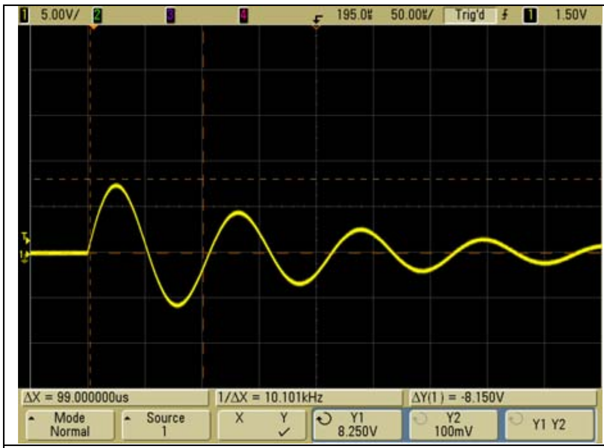


Fig. 3.3 (CB-1, CB-2, CB-3), Charging voltage:16.7 kV, Peak current: 138kA, Frequency: 9.43 kHz with field shaper

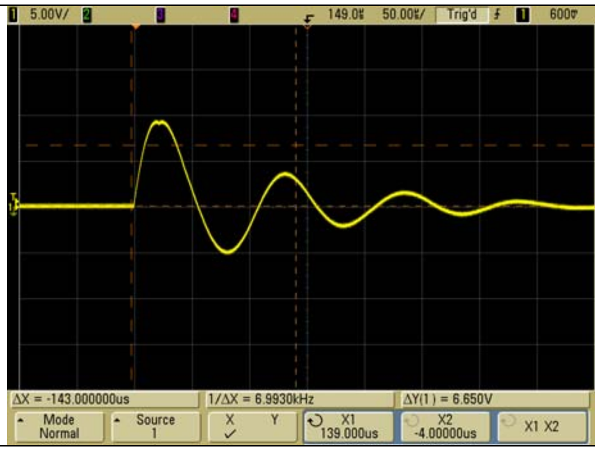


Fig. 3.4 CB-1, CB-2, CB-3 & CB-4, Charging voltage: 19kV, Peak current: 165kA, Frequency: 9.1 kHz with field shaper

4. Safety Practices

In the operation of any high voltage, high current pulse power system like Energy Storage Capacitor Bank; likelihood of Electrical, Mechanical and Sonic Hazards always exist. The sudden release of high levels of electrical energy can create hazards that range from thoroughly unnerving to potentially lethal in their effects. The safety guidelines given in IEEE Standard 510-1983, which describes the safety practices with regards to electrical hazards and cautions all personnel dealing with high voltage applications and measurements, should be strictly followed. It is in this context some of the following safety practices are listed which should be rigidly adhered to safeguard person and equipment [12].

1) Adequate Insulation must be provided and maintained between points of substantial different potential.

2) Ensure storage capacitor Bank, power supply and control panel racks doors and coverings are bonded to the cabinet with heavy duty straps and should be securely screwed.

3) Energy storage capacitors and associated circuitry should be interlocked with cabinet doors and panels so as to be firmly grounded when the cabinet is opened. The IS-3043, 1987 titled 'Code of Practices for earthing' should be followed.

4) Maintenance personnel should work on energy storage circuitry only after firmly shorting the storage capacitors with a direct wire connection.

5) All standard precautions when working with high-voltage components should be observed by maintenance personnel.

6) The load should preferably be encased in strong non-metallic /metallic shells

7) The intensity of sound generated could be great enough during possible load failure or shorting so as to cause damage to ears of nearby personnel. A sound absorbing barrier should be placed around work station to avoid this hazard. Ear-muffs should always be used by the operator. OSHA noise regulations should be followed.

8) Console or control panel and power supply racks are to be spaced from that of the capacitor bank rack by a minimum of about 10M and the operator should face the system so as to detect any spurious arcing during energy discharge, through the panel door crevices. Such spurious arcing, as a result of induced high rates of voltage and current charges across the loose panel frames/doors is a potential fire hazard and should be avoided by proper panel/door fixings.

4.1 General Safety Guidelines:

Electromagnetic Manufacturing setups being a high voltage setup, the safety measures related to high voltage safety are very important. The danger is most lethal in the body providing a conducting path, particularly through the heart. Also any involuntary muscle contractions caused by a shock, while perhaps harmless in them, may cause collateral damage. There are likely to be many sharp edges and points inside setup like metal inserts, nut bolts, metal sheets and left out spanners or other such instruments on the setup which may be lethal if not properly taken care. In addition, the reflex may result in contact with other electrically live parts and further unfortunate consequences. The guidelines mentioned below help to protect one-self from potentially deadly electrical shock hazards as well as the equipment from accidental damage.

1) Don’t work alone - in the event of an emergency another person's presence may be essential.
2) Wear rubber bottom shoes or sneakers. An insulated floor is best option than metal or bare concrete but this is sometimes difficult to maintain. A rubber mat is an acceptable alternative. No carpet of any thickness will serve as insulator.

3) Try to keep one hand in your pocket when working anywhere around a powered line-connected or high voltage system. Wear ear muffs for the protection from the spark gap triggering sound.

4) Wear eye and head protection - large plastic lensed eyeglasses or safety goggles and helmet.
5) Don’t wear any jewel or other articles that could accidentally contact circuitry and conduct current.
6) Stand away from the setup behind the protection wall to protect oneself from the exposure to Electromagnetic field and the stray components, if any, which may accelerate like bullets
7) Always keep the capacitor banks shorted when not in use.
8) Make sure to dump all the charge on the capacitor.
9) Manual dumping by using a dead stick confirms the complete discharge of the capacitors.
10) Do not use the capacitors to its full rating to avoid the explosion of capacitors due to weakening of the capacitor wall after repeated use.
11) Have a fire extinguisher rated for electrical fires readily accessible in a location.
12) Finally, never assume anything without checking it out. Avoid taking shortcuts and monotony.

5. Typical EM Forming and Welding Applications

The feasibility of EMF/EMW technology has been demonstrated for many in house and general applications and the competence has been firmly established. The applications are Electromagnetic forming/welding of metal sheets, tubular expansion and compression and welding of similar and dissimilar metals. The Table 1 gives an idea of the typical ranges of job sizes with various materials and the corresponding requirement of the capacitor bank energy for the EMF/EMW process. The following gives a brief account of typical applications on EM Forming and Welding. This is provided as an example and by no means covers the huge field of applications.

Applications using Flux Concentrator: Specially made strong coils called 'Flux Concentrator' were used for EMF applications. The photograph of one such Flux Concentrator is shown in Fig 5.1. It consists of a primary winding placed in the grooves made in solid slug. The latter having a longitudinal slit, (tapering towards the centre) acts as secondary. Materials like brass or duraluminum are used for the slug. This kind of arrangement, results in the enhancement of magnetic field in the central bore of the slug. However the longitudinal slit reduces the strength of the coil.

A wide variety of EM formations were conducted. Some illustrative are in the photographs in Figs 5.2, 5.3 and 5.4 shows Aluminum plugs to aluminum rod collapsed joints, Copper lug swaged on to the aluminum multi-core cable and Aluminum plug collapsed on to SS-rod.

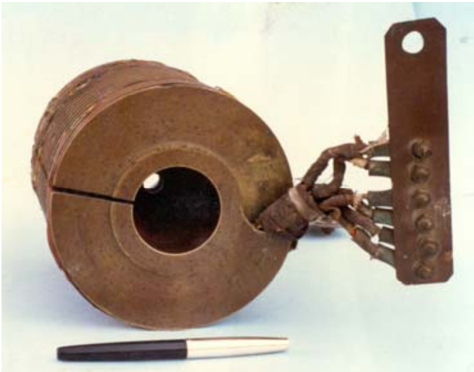
Welding of thin flat sheets: The EM welding technique has great potential in many industrial (such as aerospace and automotive) applications, especially for joining the materials with large difference in their melting points. Electromagnetic Welding of 1mm thick flat sheets of various metals such as Al-Al, Al-SS, Al-Cu, and Al-Al (alloy) were successfully demonstrated. The Fig 5.5 shows the EM welding setup and Fig 5.6 shows the EM Welding coil setup with sample sheet mounted. EM welds were carried out using a 10 kJ, 10 kV capacitor bank. Aluminum was found to be the easiest to weld and it was used as driver for achieving welds in other metal combinations [13].

A wide variety of EM Welding were conducted using 1mm thick flat sheets of same and different metals. Some illustrative ones shown in the photographs, Figs 5.7, 5.8 and 5.9, show Al-Al sheet welding, Cu-Cu sheet welding and Cu–SS sheet welding respectively. The (Cu-Al) welded samples were tested for their shear strength with uni-axial tensile testing

Table 1

EMF/EMW Jobs sizes on various materials and the Capacitor Bank Energy requirement

Material	**Geometry**	**Capacitor Bank Energy**		
		10kJ	**20kJ**	**40kJ**
Al (Aluminum)	Tubular	Ranging from 10 mm Ø, 1mm to 6 mm Ø, 3mm thick	Up to 60 mm Ø, 5mm thick	60 mm Ø, 7.5mm thick.
	Plate/Strip	30 mm x70 mm 2mm thick	50 mm x100 mm 3 mm thick.	-----------
Cu (Copper)	Tubular	Ranging from 10 mm Ø, 0 .5 mm, up to 60 mm Ø, 1mm thick.	60 mm Ø, 2 mm thick.	60 mm Ø, 3.2 mm thick.
	Plate/Strip	30 mm x 70 mm, 0.5mm thick.	50 mm x 100 mm, 1mm thick.	------------
SS (Stainless Steel)	Tubular	Ranging from10 mm Ø, 0 .2 mm thick, up to 60 mm Ø, 0 .8 mm thick	60 mm Ø, 1.5 mm thick	6 mm Ø, 2.5 mm thick.
	Plate/Strip	30 mm x 70mm, 0.3 mm thick	50 mm x 100 mm, 1.5 mm thick.	-----------
Zr (Zirconium)	Tubular	-------------	70 mm Ø, 3 mm thick	----------



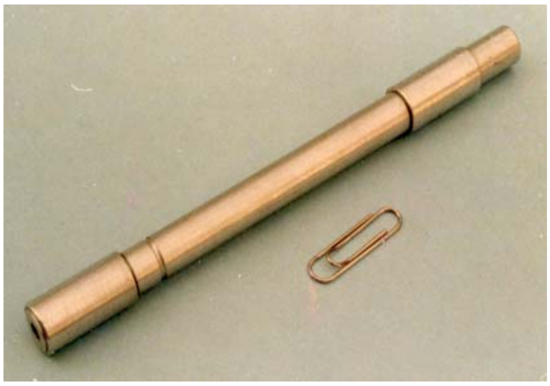
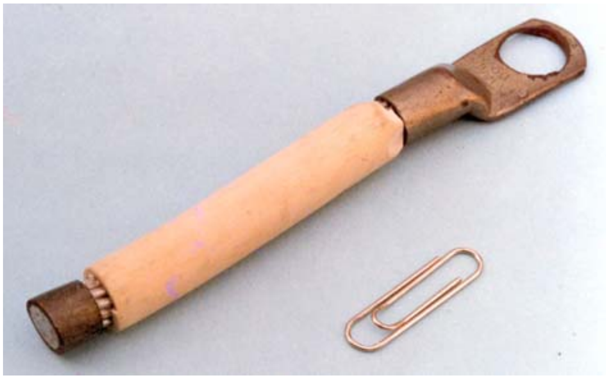


Fig 5.1 Magnetic Flux Concentrator

Fig 5.2 Two Al plugs collapsed at two ends of Al rod



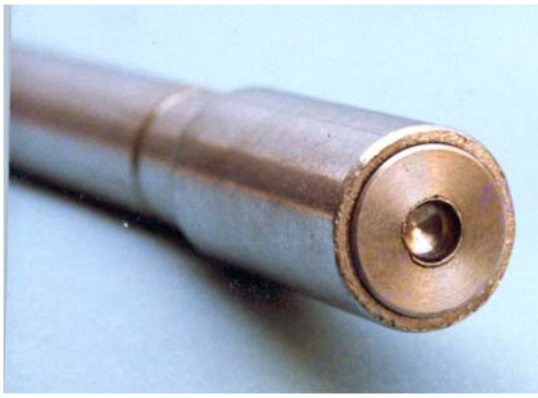
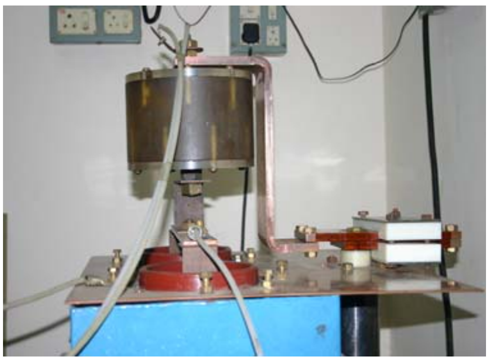


Fig 5.3 Copper lug swaged on Al-multi-core cable

Fig 5. 4 Al-plug collapsed on SS-rod



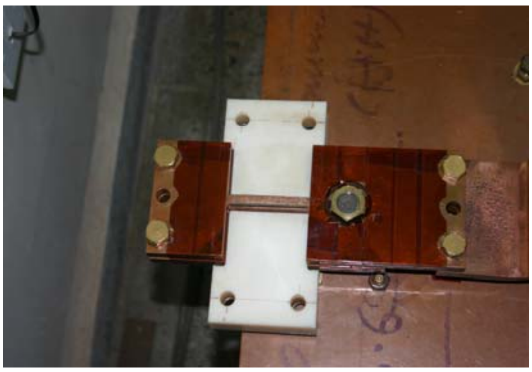


Fig 5.5. EM Welding setup for sheet samples

Fig 5.6 EM Welding coil for flat sheet to sheet

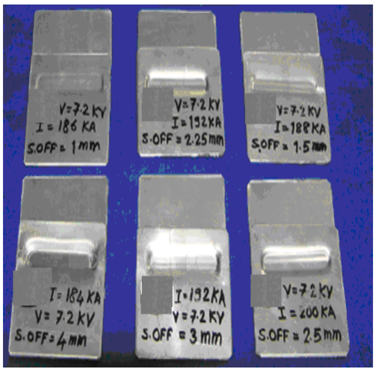


Fig 5.7 Al-Al sheets EM welded samples

Fig 5.8 Cu -Cu sheets EM welded samples

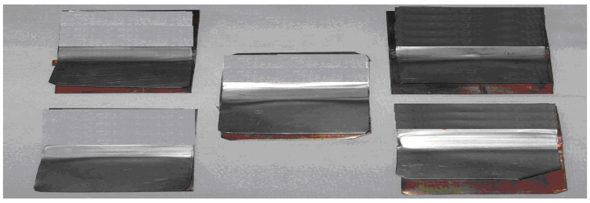


Fig 5.9 Cu -SS sheets EM Welded Samples

Fig 5.10 Tensile Testing of Al-Cu EM welds

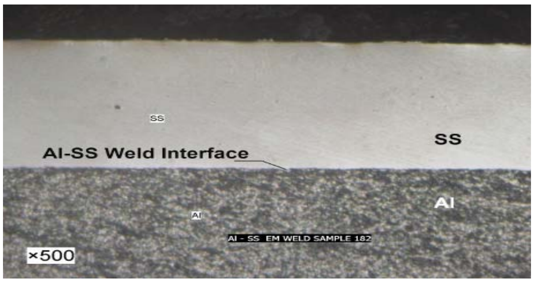


Fig 5.11 Magnified View of the Weld Zone

Fig 5.12 Micrograph of Al Clad to End Plug (150x).

machine and observed under the microscope for the weld interface The tensile shear strength of the weld was found to be 23 MPa. The tensile testing sample of Cu-Al weld failed in the parent metal indicating that the weld was stronger than the parent metal as shown in Fig 5.10. The welded samples were subsequently sectioned across the weld, polished, and etched to determine the zone of actual metallurgical continuity. The metallographic studies of all Al-to-SS welded samples welded at different sets of process parameters showed the continuous weld zone at the line of impact (Fig 5.11). A Micrograph of Aluminum Clad to End Plug Welding is shown in the

Fig. 5.12. Pulse Magnetic welding experiments on few samples of the D9 clad to SS316L end plug have been conducted. The shots were taken at 40 kJ energy. A photograph of the joined samples, one with copper driver and another after chemically etching the copper driver is shown in fig. 5.13. The sample withstood the helium leak rate better than 1.2 X 10-9 mbar Lit/sec.

Fig.5.13 Joined samples of the D9 clad to SS316L end plug

6. Acknowledgment

The authors thank Shri S. V. Desai for his electromagnetic welded samples for thin sheet metals and Shri S. Mitra for his suggestions on synchronization of spark gap switches. The authors also thank Smt S.R. Barje for preparing the drawings and Shri N. Lawangare, Shri S.P.Vaity and Shri S.G.Patil for their technical support.

7. References:

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[10] Pulsed High Magnetic Field, Heinz Knoephel, North Hollond Publishing Company, 1970.

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[12] IEEE STD 510-1983 IEEE, Recommended practices for safety in High Voltage and Power Testing.

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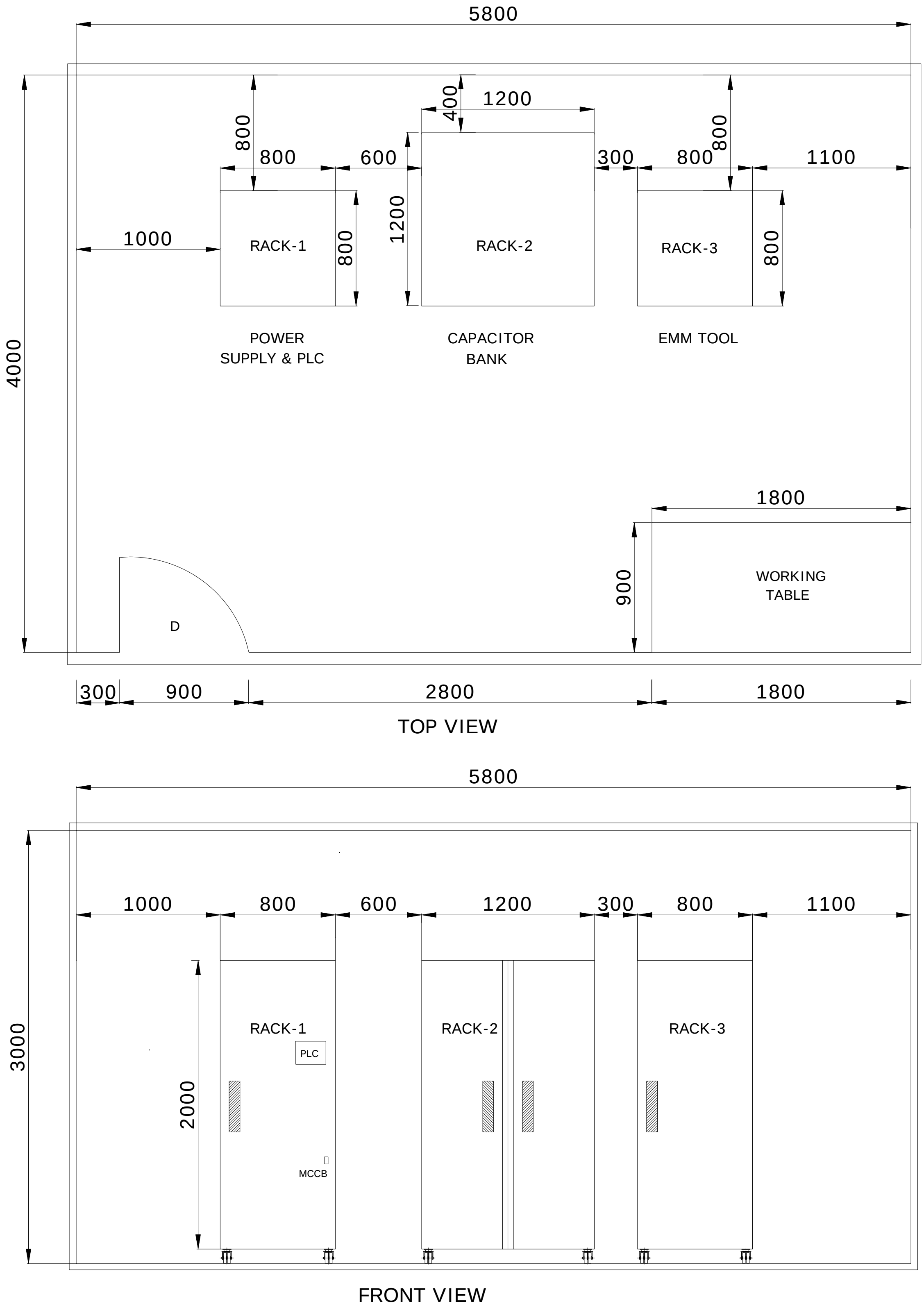
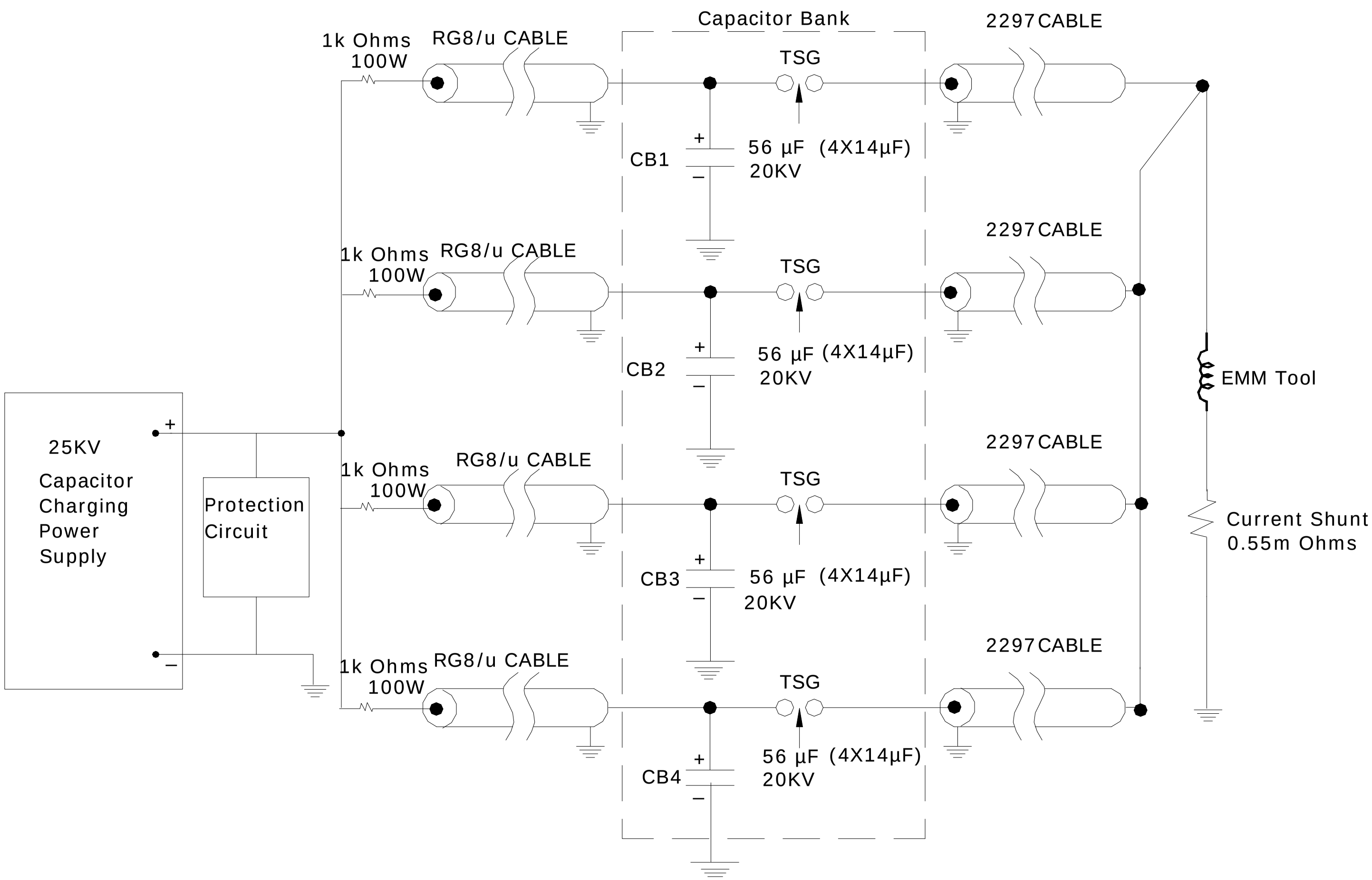
Appendix-A

Circuit and wiring diagrams

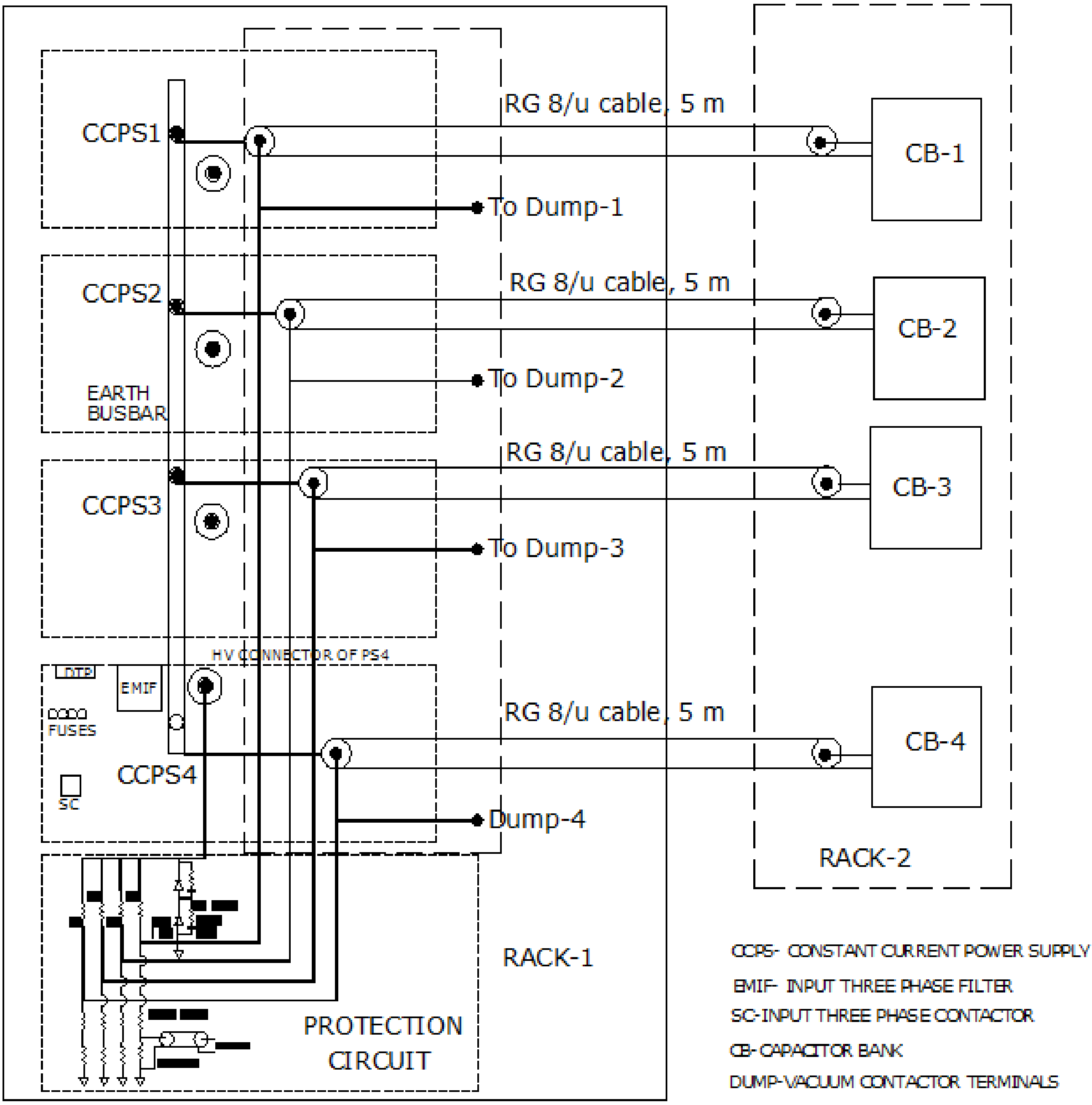
A1: Photograph of the 40kJ, EMM Equipment



A2: General Layout of 40kJ EMM Equipment



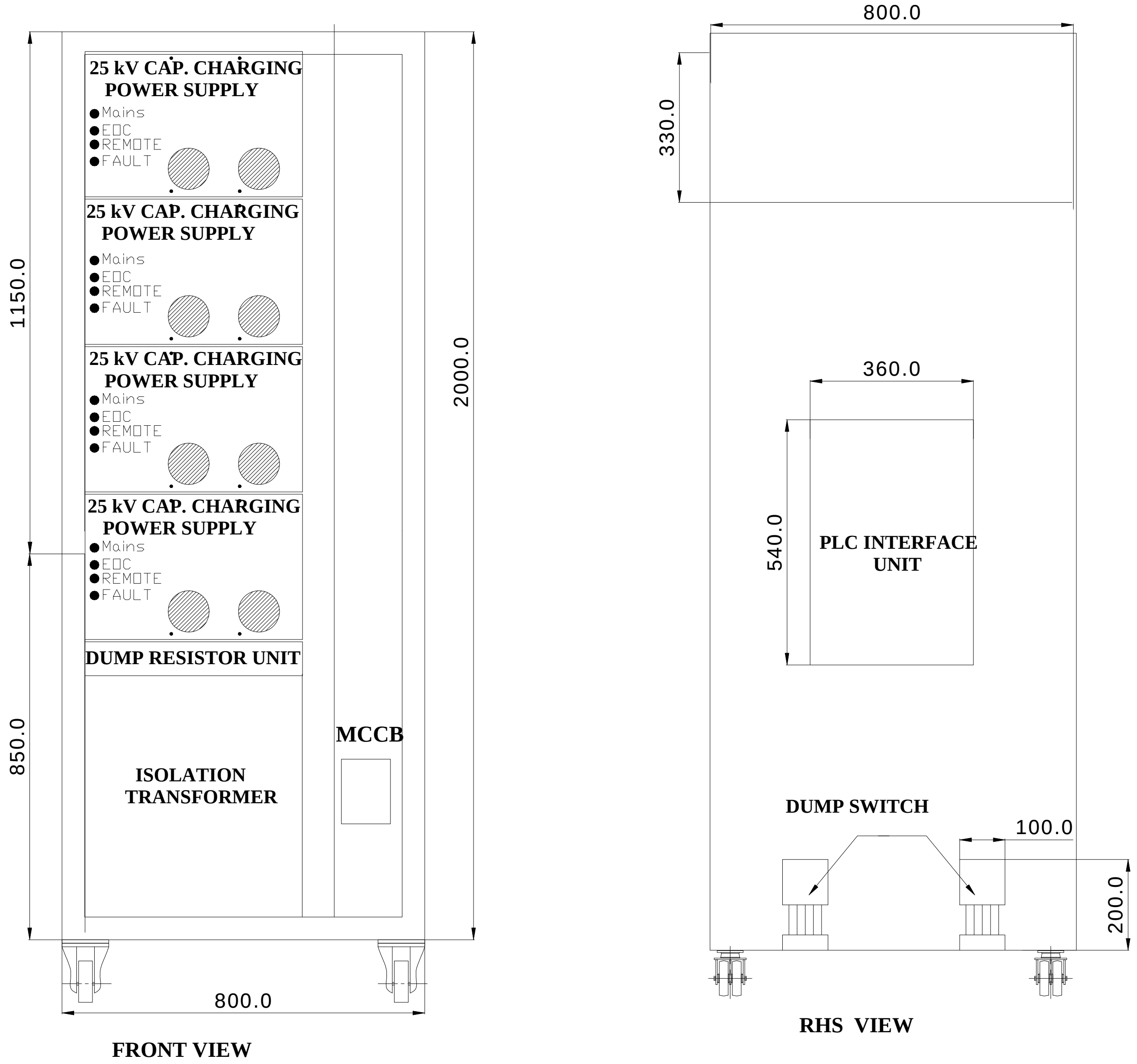
A3: Wiring Connection Diagram of Power Supply, Capacitor Bank and EMM Tool



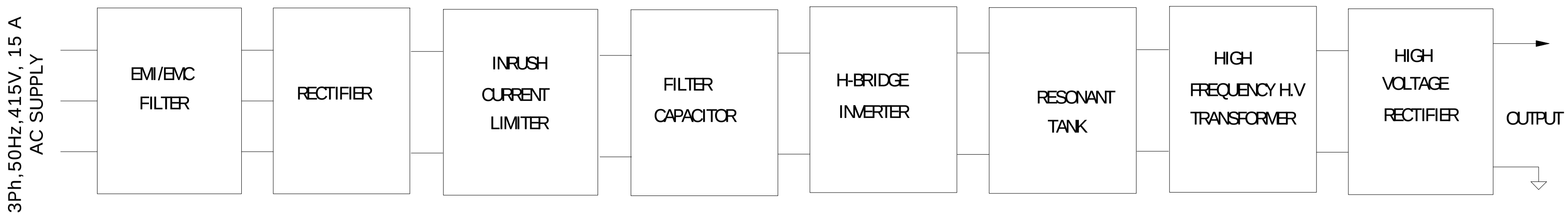
A4: High Voltage interconnection diagram between power supply and capacitor bank

Appendix-B

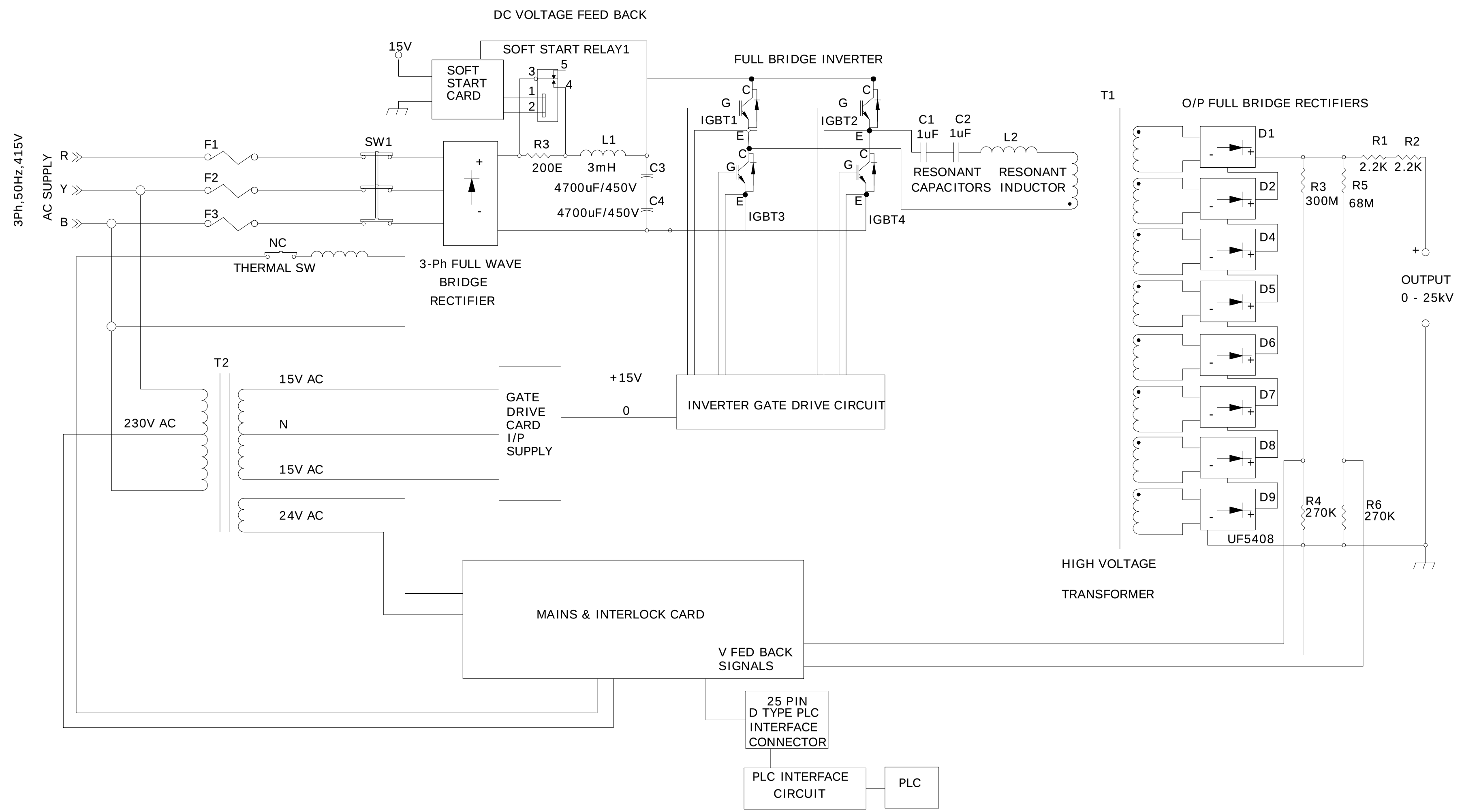
Assembly, layout drawings and interconnection diagrams in Rack-1



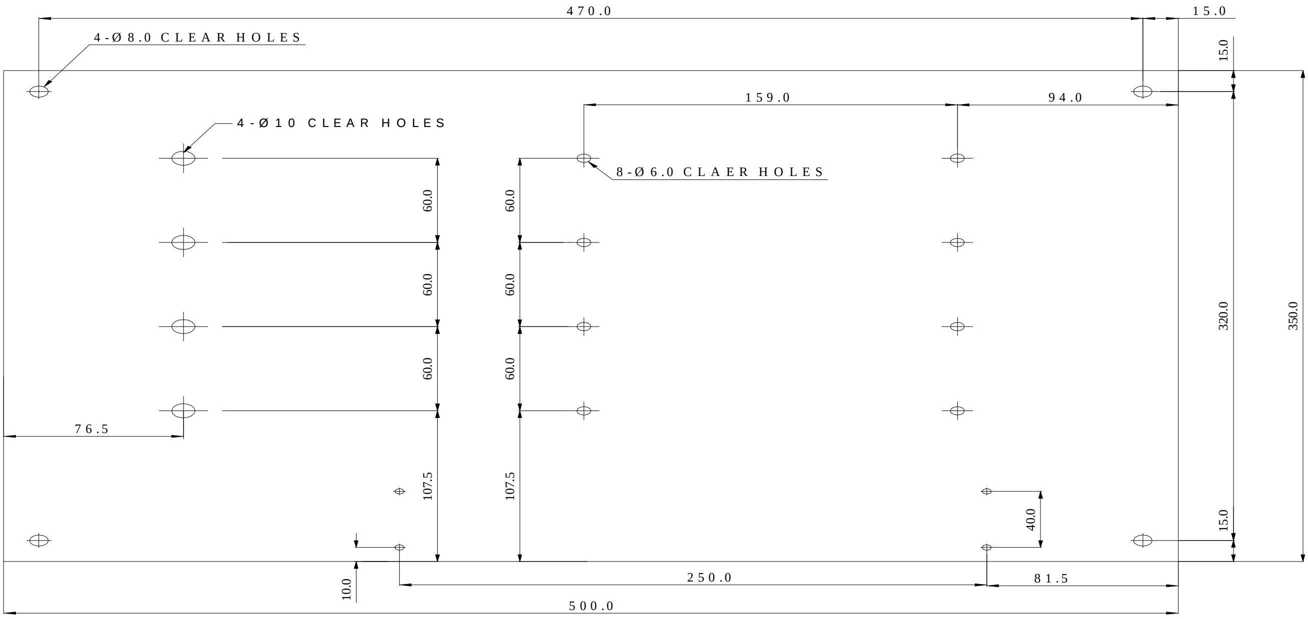
B1: Assembly Layout of Power Supply, PLC Controls and Dump Switch in Rack-1



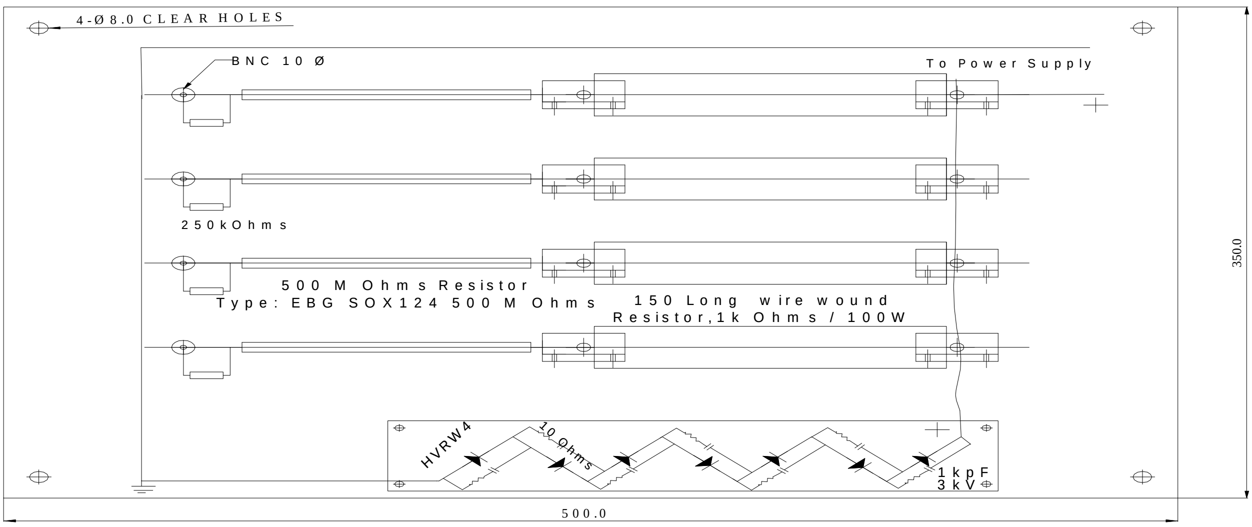
B2: Block diagram of CCPS Power Supply Unit.



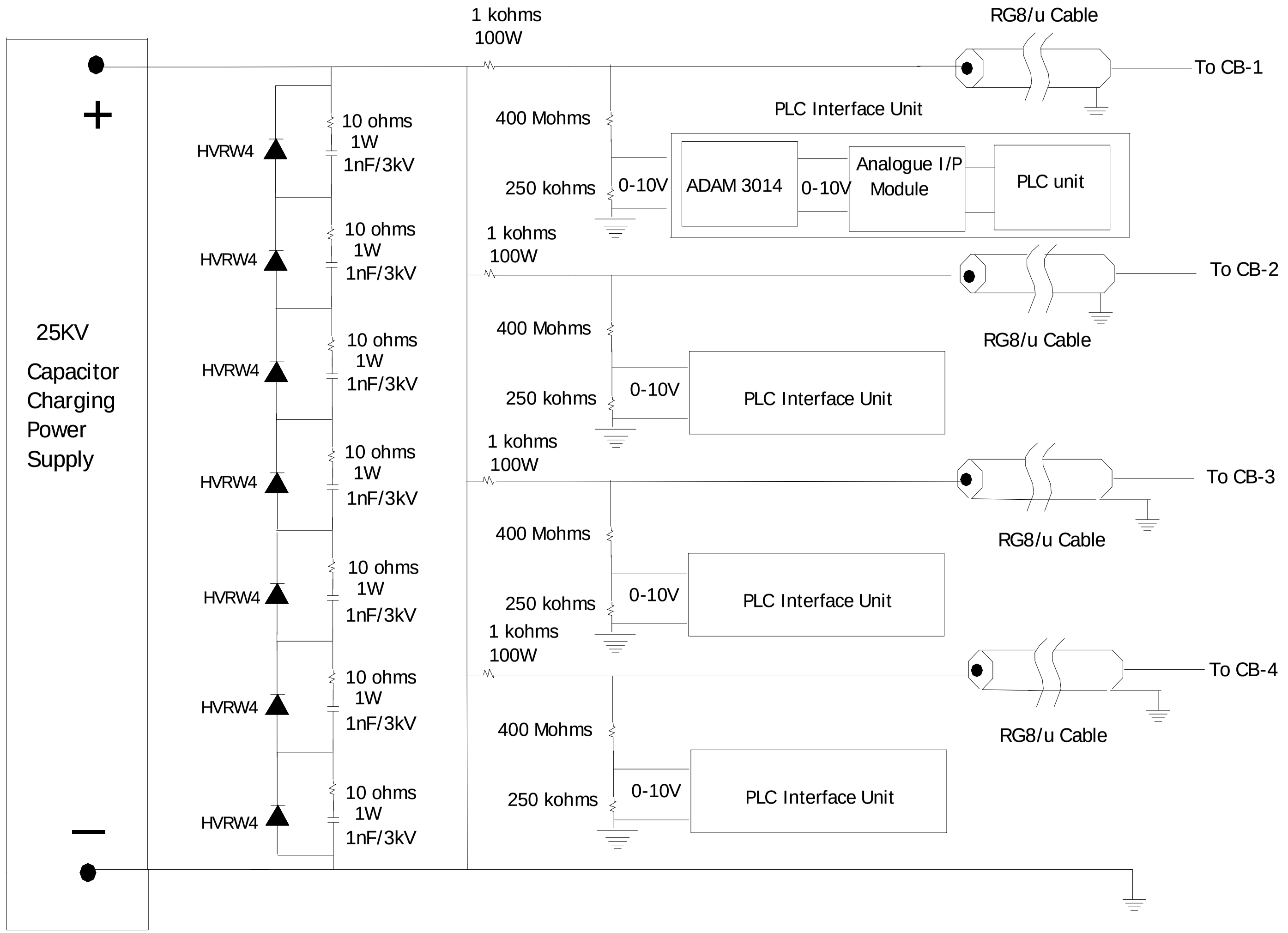
B3: TYPICAL SCHEMATIC DIAGRAM FOR 25kV CCPS & PLC INTERFACE



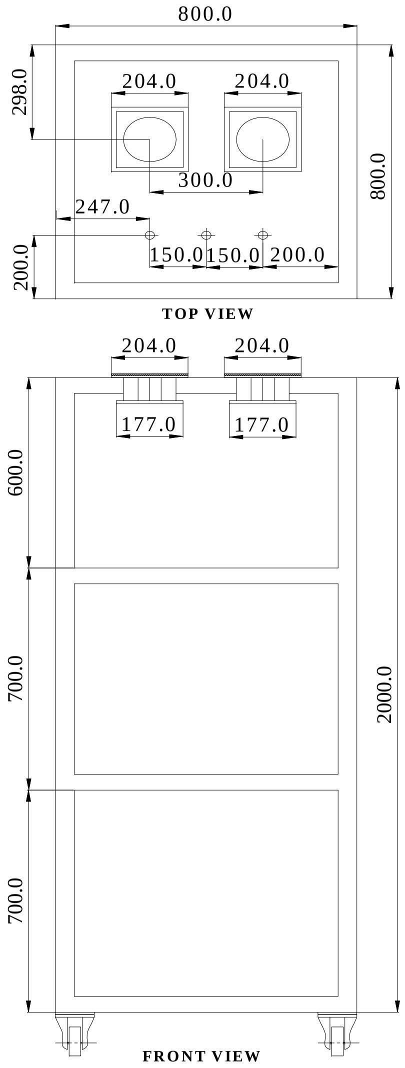
FRP,6mm Thick
QTY:-1 NO



B4: Power Supply Protection Circuit Assembly



B5 Schematic Diagram of Protection and Voltage Divider Circuit



Sl. No.	Item Description	Qty
1	EMC enclosure based on TS of dimensions 800W X 2000H X 800D with ≥ 40 dB for magnetic field at 100kHz and ≥ 70 dB for electric field shielding up to 1 MHz	1
2	Castors 2 numbers with brakes and 2 numbers without brakes.	1
3	Side panels fixed screw type un vented for 2000H X 800D (pack of 2)	1
4	Tube light 14W, 230V AC, 50 HZ with connection cable and micro switch	1
5	Door Operated switch with connection cable.	1
6	EMC Cable gland 2/ rack.	2
7	17X23 Punched section (pack of 4)	1
8	Comfort handle.	1
9	Key insert	1
10	EMC fan and Filter.	1
11	EMC Filter	1
12	System Support rails (pack of 2)	1

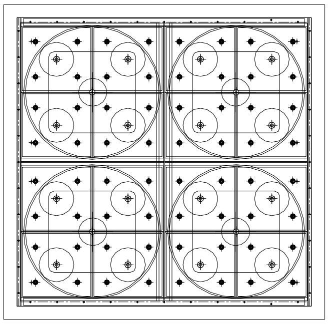
<u>Additional Features & Accessories:</u>

(i) EMI gasket to be provided at all mating surfaces.
(ii) Door: Double front and rear door with rod type locking facility
(iii) Protection class: IP-54
(iv) Bottom Supports: To be provided with heavy duty castor wheels with locking facility. (Internal components weight of EMC rack is about 2 Ton & control rack is about 500kgs)
(vi) Lifting bolts: I-bolts capable of lifting the assembled unit.
cable manager 2 numbers of 1U size (in top and middle compartments) and cable channels 1 inch x 1 inch, on 2 sides for entire height and top across the width.
(v) 50 Nos. Captive mounting hardware.
(vii) Cutout for cable entry (Location will be decided at the time of fabrication)
(viii) Inspection and testing for RF shielding effectiveness certificate to be given by the manufacturer.

B6: Rack-1 Frame Details

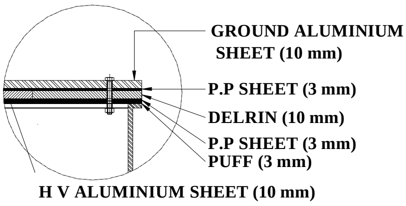
Appendix-C

Assembly, layout drawings and interconnection diagrams in Rack-2

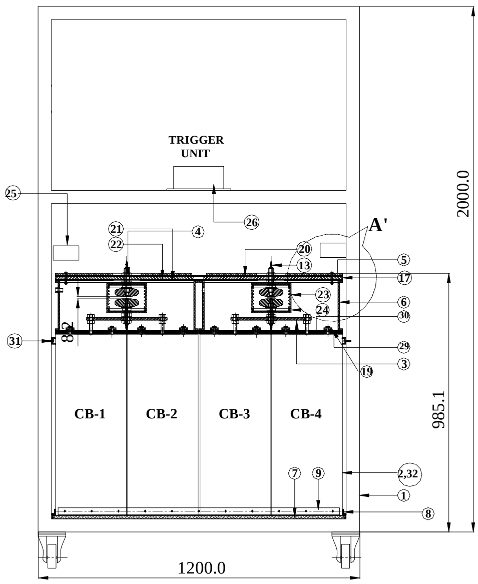


TOP VIEW

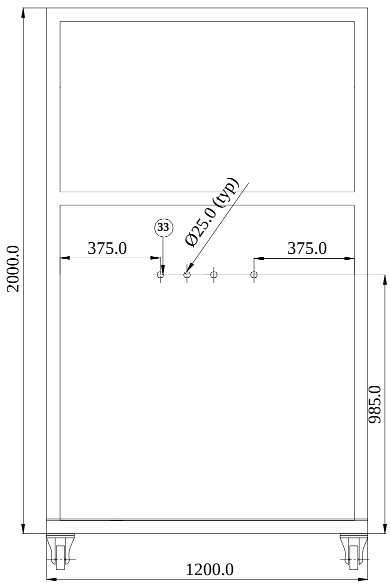
DETAIL AT A'



BILL OF MATERIALS					
S.R. No	PART No	DESCRIPTION OF THE MATERIALS	MATERIAL	QTY	REMARK
1	1	CAPACITOR RACK OF SIZE (1200X1200X2000)MM	MILD STEEL	1 No	
2	2	CAPACITOR (YESHA MAKE)	STANDARD	16 Nos	
3	3	HV CAPACITOR TOP PLATE (325X252X12) MM	ALUMINIUM	04 Nos	
4	4	HIGH CURRENT COPPER STRIP LINE CONNECTIONS	COPPER	04 Nos	
5	5	GROUND PLATE (1073 x 1060)	ALUMINIUM	01 Nos	
6	6	COAXIAL CHAMBER FOR SPARKGAP	ALUMINIUM	04 Nos	
7	7	CAPACITOR BASE PLATE	DELRIN	01 No	
8	8	SUPPORT ANGLE FOR CAPACITORS	SS304	02 Nos	
9	9	SUPPORT ANGLE FOR CAPACITORS	SS304	02 Nos	
10	10				
11	11				
12	12				
13	13	SPARKGAP ASSEMBLY	SS304L	04 Sets	
14	14				
15	15	METAL CHAMBER FOR POLY URETHENE FILM	ALUMINIUM	04 Sets	
16	16				
17	17	PACKING PLATE OF SIZE (150X84X10)MM	PP	04 Nos	
18	18				
19	19	SPACER FOR CAPACITOR	SS304	64 Nos	
20	20	STRIP LINE HV INSULATOR-SIZE (1073X1060X3)MM	POLY PROPELENE	01 No	
21	21	STRIP LINE HV INSULATOR (1073X1060X3)MM	POLY PROPELENE	01 No	
22	22	STRIP LINE HV INSULATOR PUF (1073X1060X3)MM	POLY URETHENE	01 No	
23	23	SPARKGAP ENCLOSURE	DELRIN	04 Nos	
24	24	COVER FOR SPARKGAP ENCLOSURE	DELRIN	04 Nos	
25	25	TRIGGER PULSE TRANSFORMER	STANDARD	04 Nos	
26	26	IGBT BASED TRIGGER UNIT	STANDARD	01 No	
27	29	PACKING PLATE-POLY PROPELENE	POLY PROPELENE	02 Nos	
28	30	PACKING PLATE-POLY URETHENE	POLY URETHENE	02 Nos	
29	31	SUPORT ANGLE FOR CAPACITOR	DELRIN	04 Nos	
30	32	ENERGY STORAGE CAPACITOR DETAILS	YESHA	16 Nos	
31	33	SIDE PANEL CUT OUT FOR DISCHARGE CABLE		04 Nos	

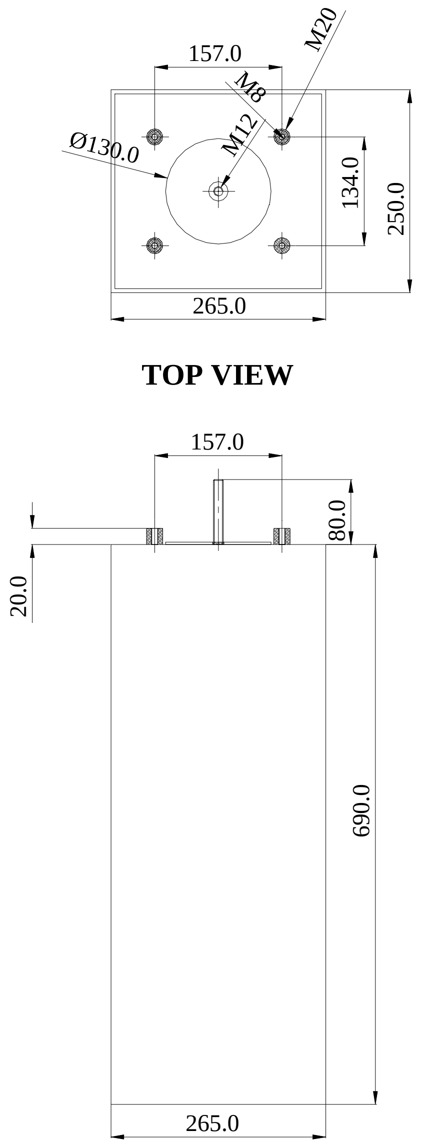


FRONT VIEW



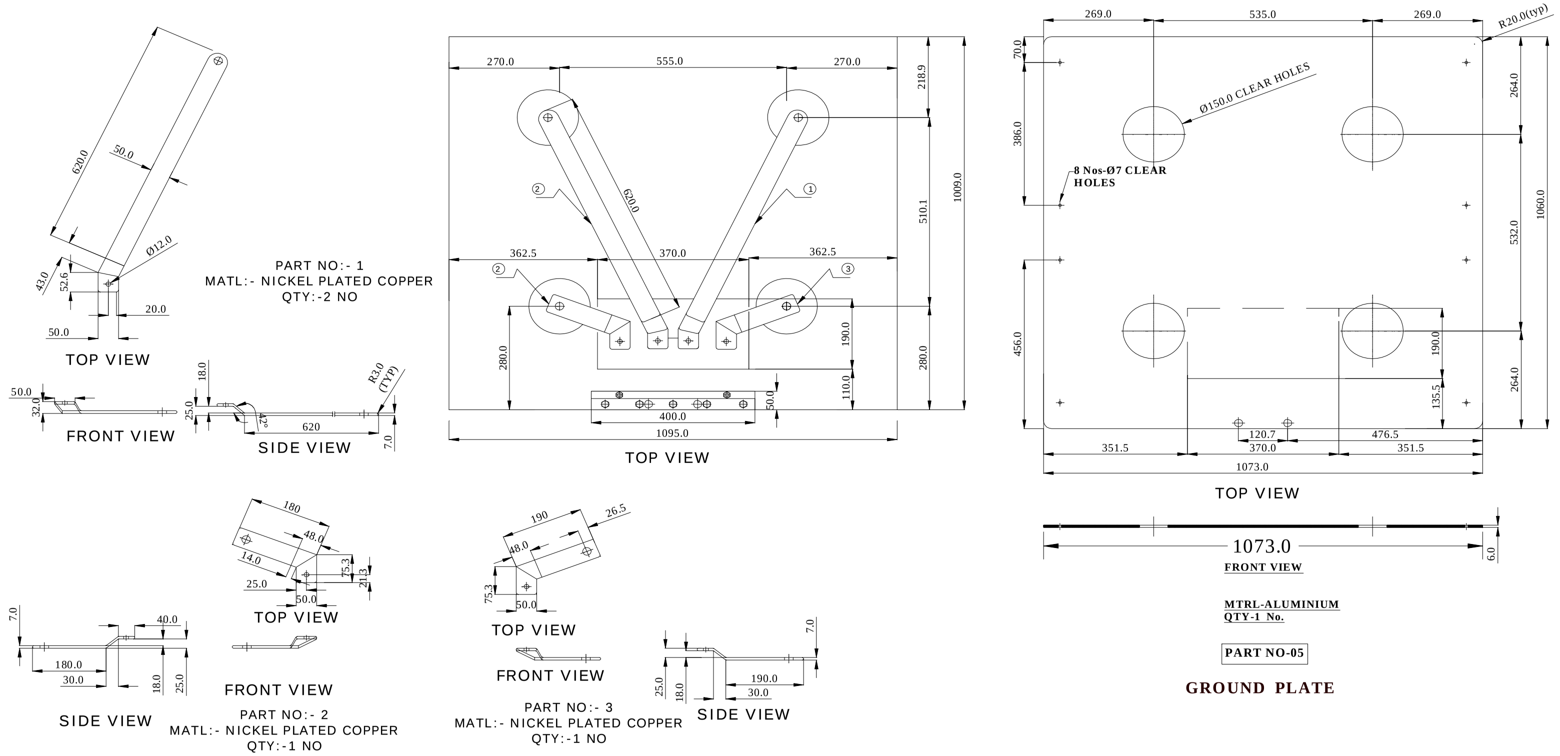
SIDE VIEW

C1: ASSEMBLY LAYOUT OF CAPACITOR BANK IN RACK-2

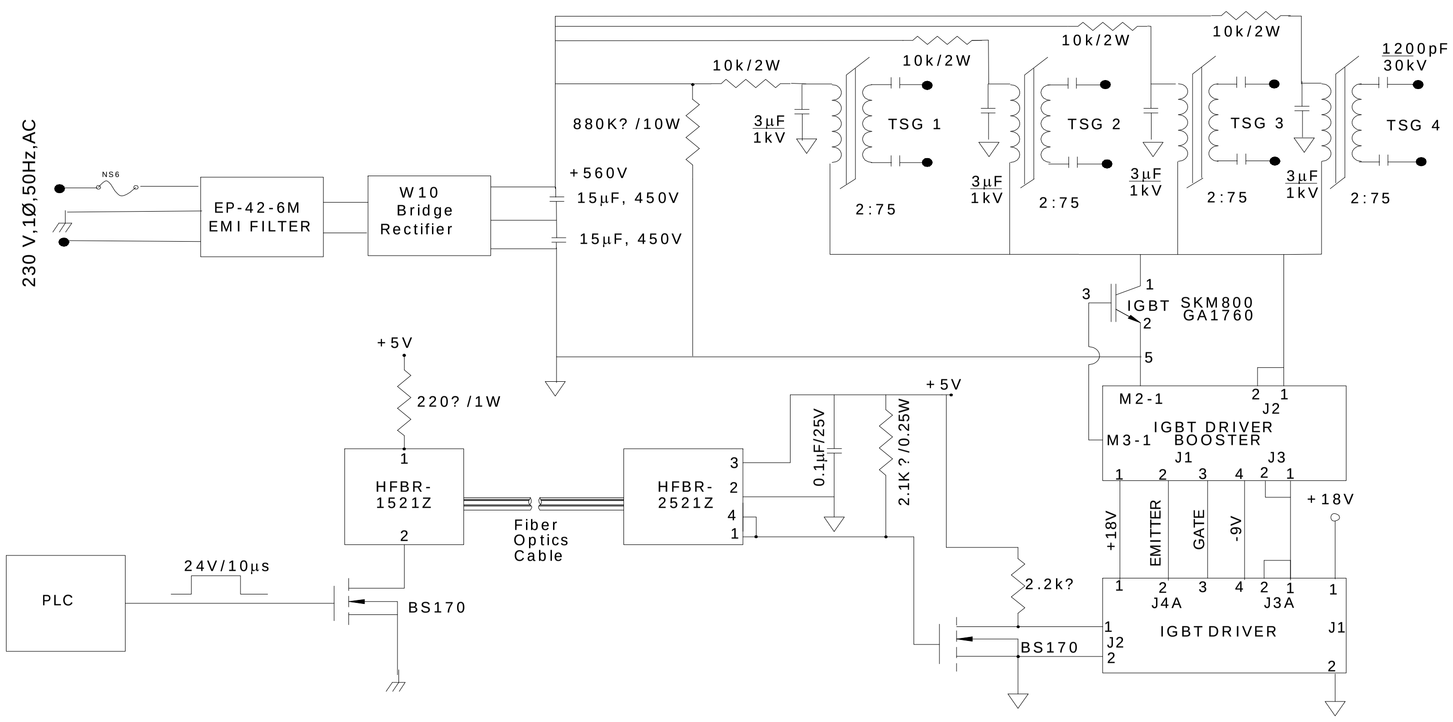


CAPACITOR (YESHA MAKE)
PART NO-32
QUANTITY-16 Nos

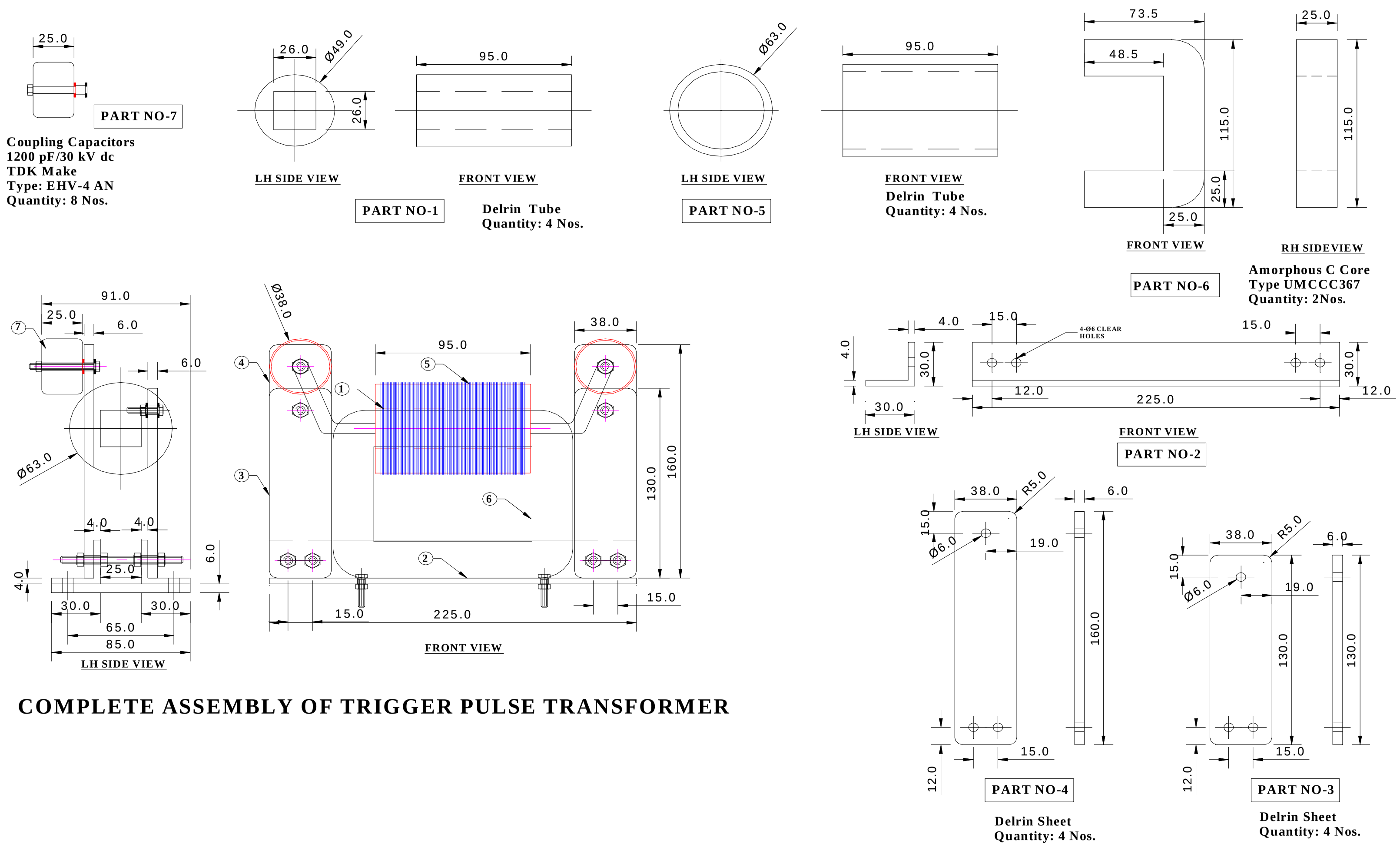
C2: ENERGY STORAGE CAPACITORS DETAILS



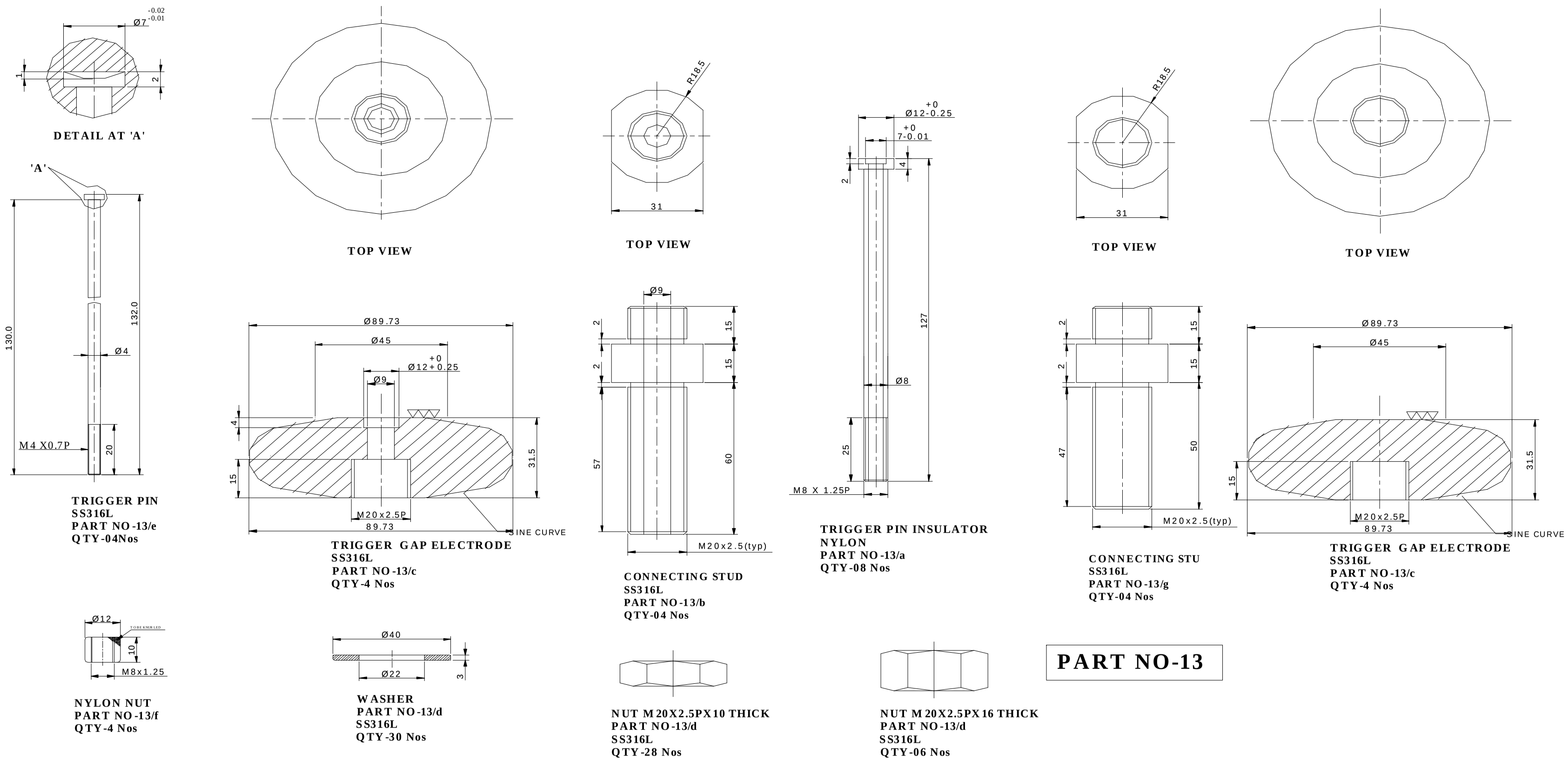
C3: High Current Strip Line Connections



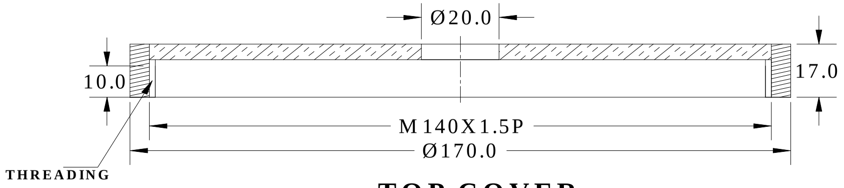
C4: TRIGGER GENERATOR CIRCUIT DIAGRAM



C5: TRIGGER PULSE TRANSFORMER DETAILS

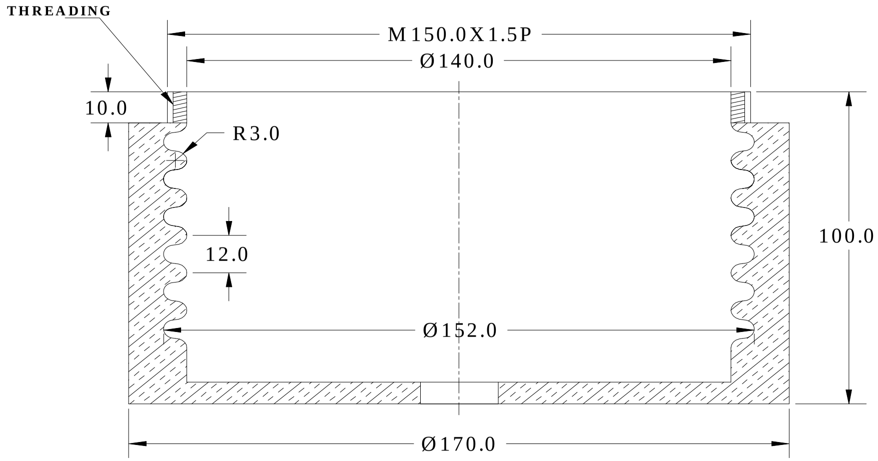


C6: TSG Component Details



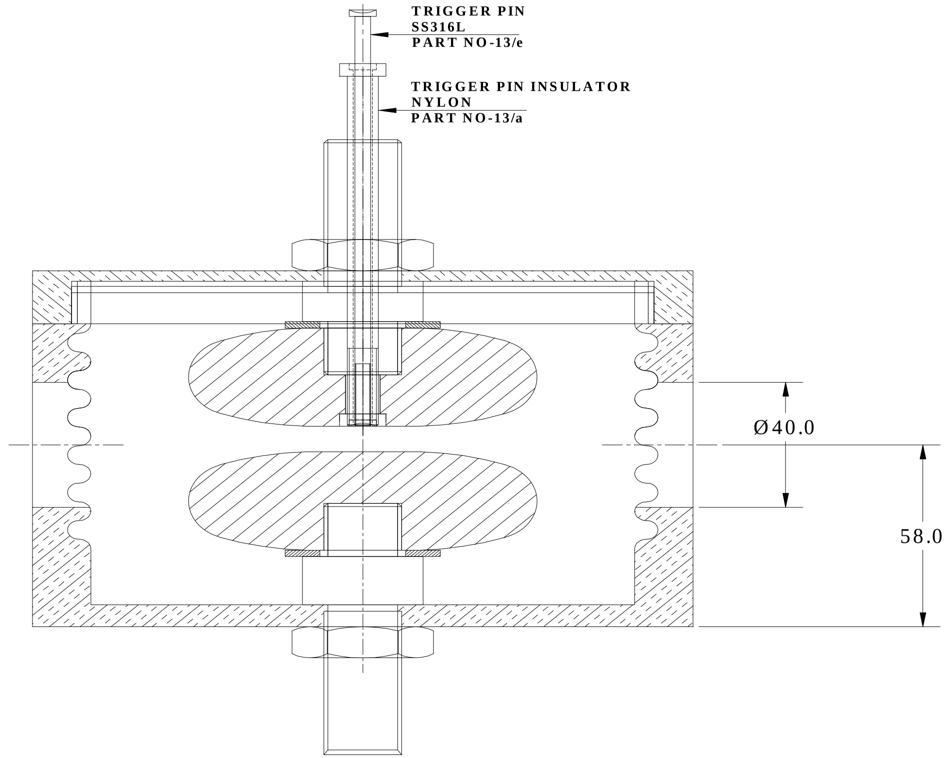
TOP COVER
QUANTITY-08 Nos

PART NO-24



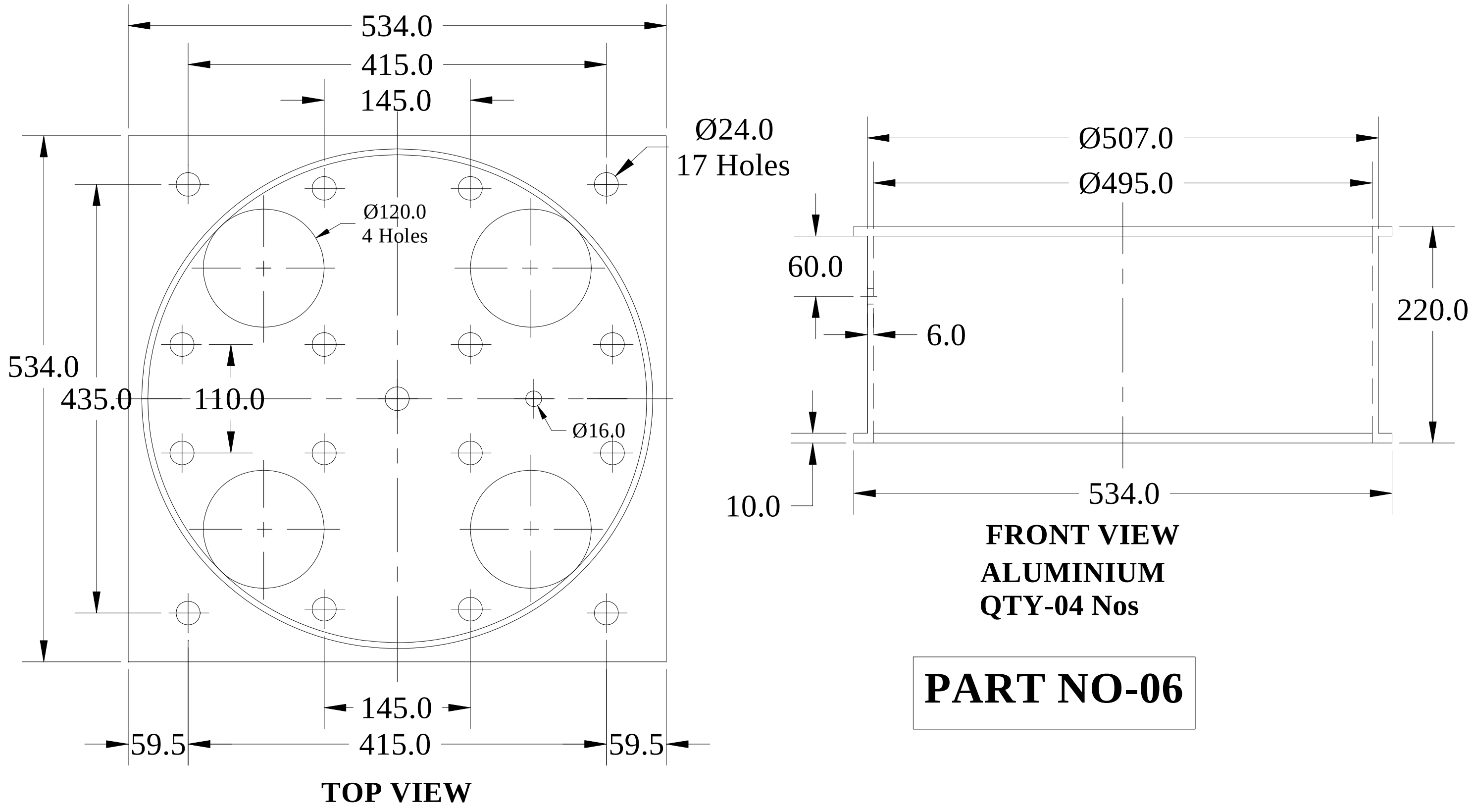
DELRIN CHAMBER
QUANTITY-04 Nos

PART NO-23

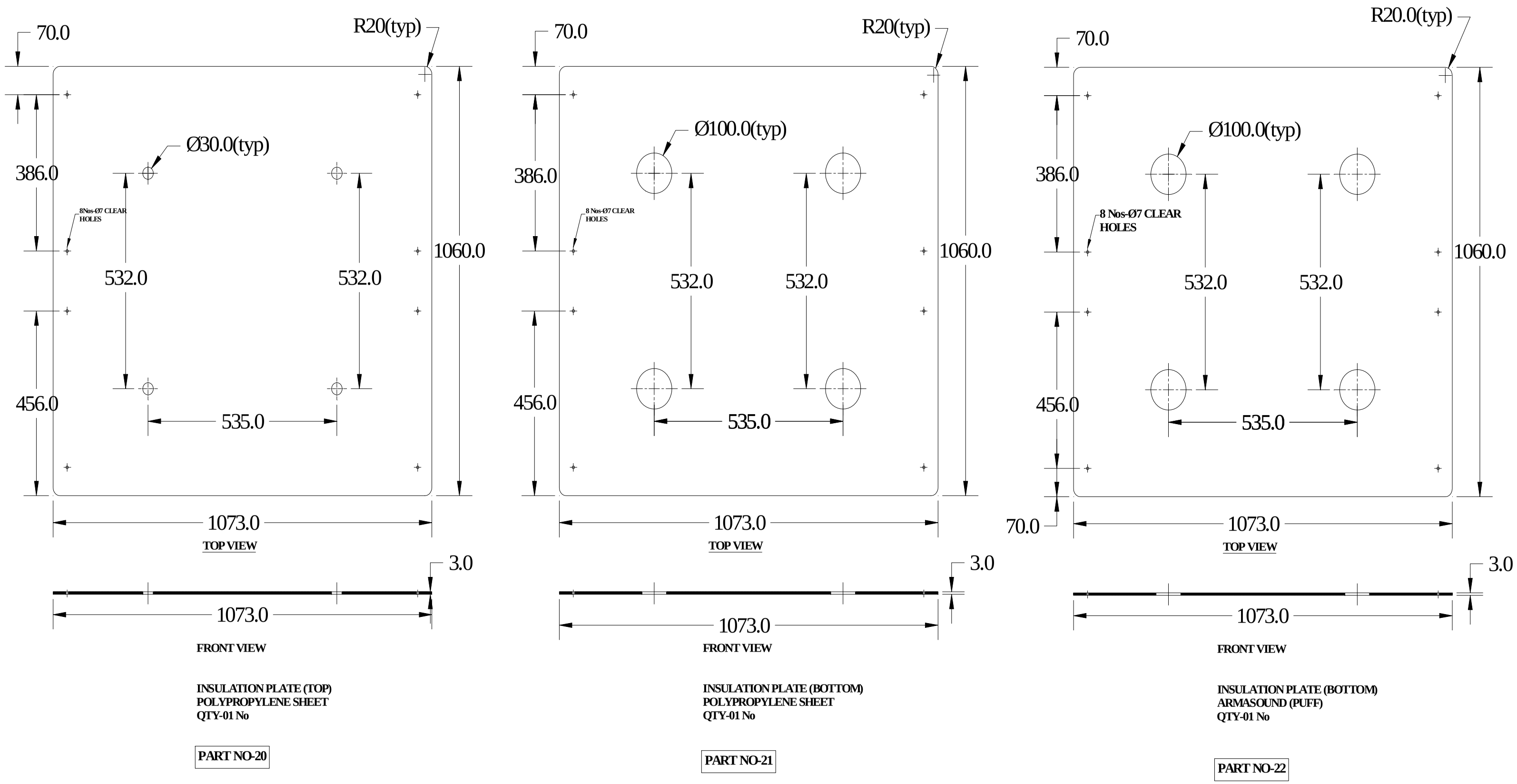


ASSEMBLY OF SPARKGAP

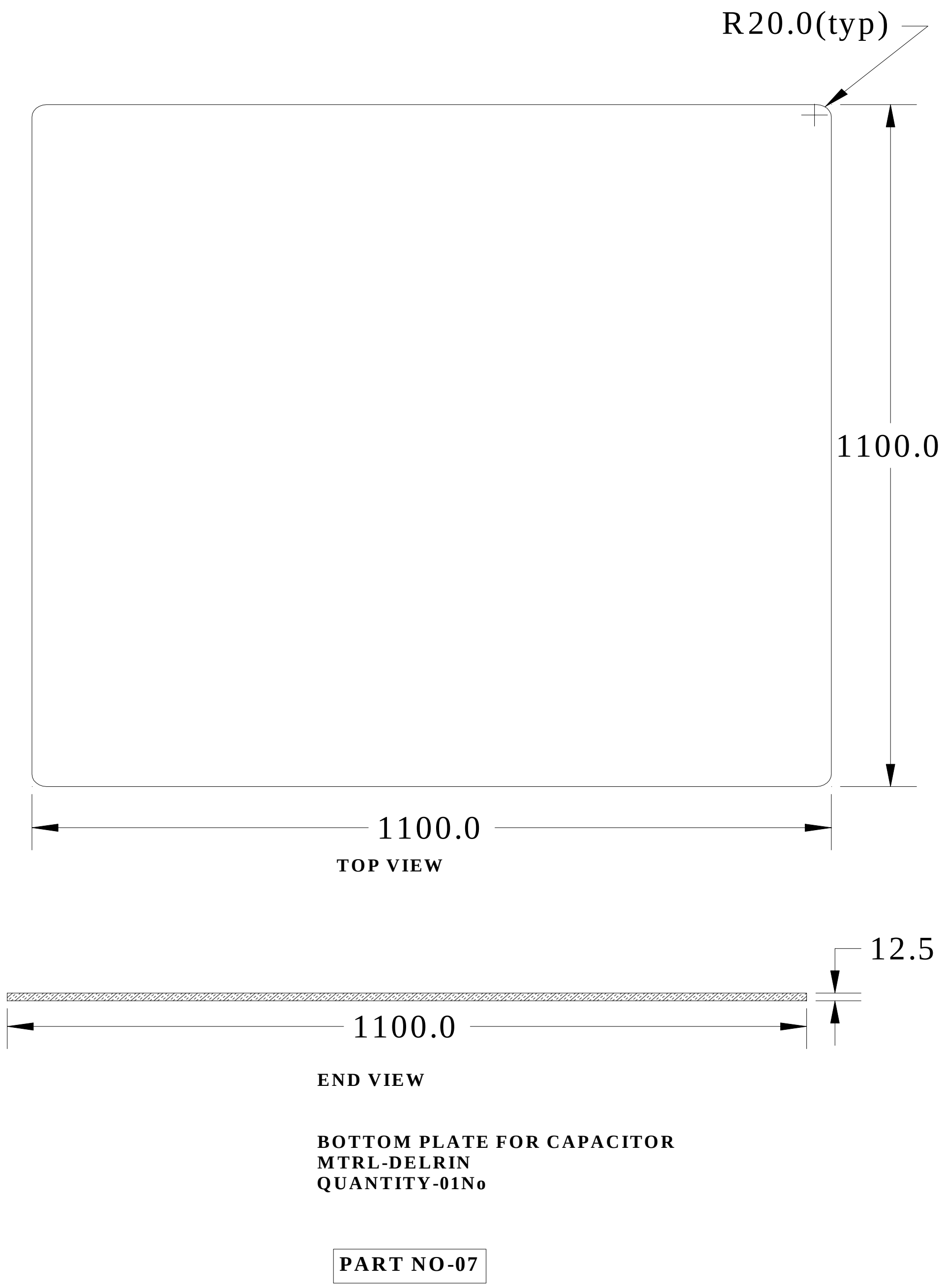
C7: TSG ASSEMBLY DETAILS



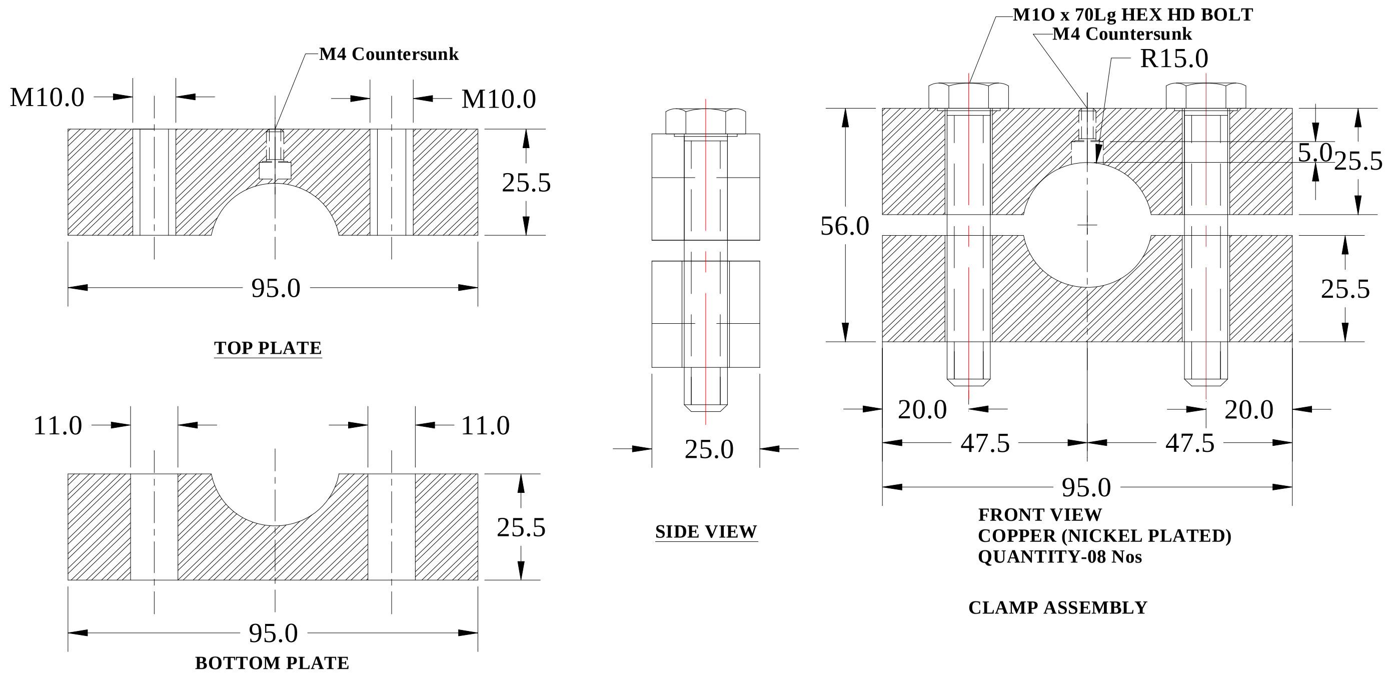
C8: Coaxial Chamber for Spark Gap



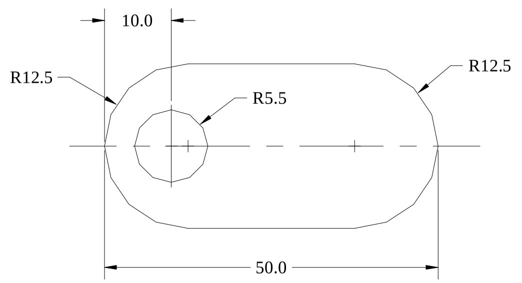
C9 Strip line HV Insulator Details



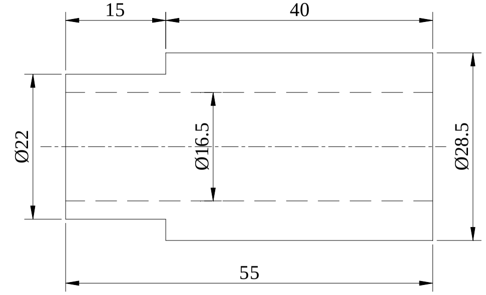
C10 Capacitor Base Plate Details



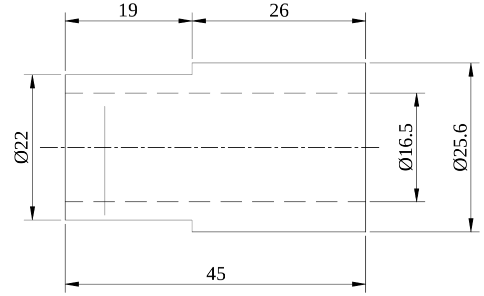
C11: High Current Cable Clamp Details



NICKEL PLATED COPPER PLATE
3mm Thick
20 NOS

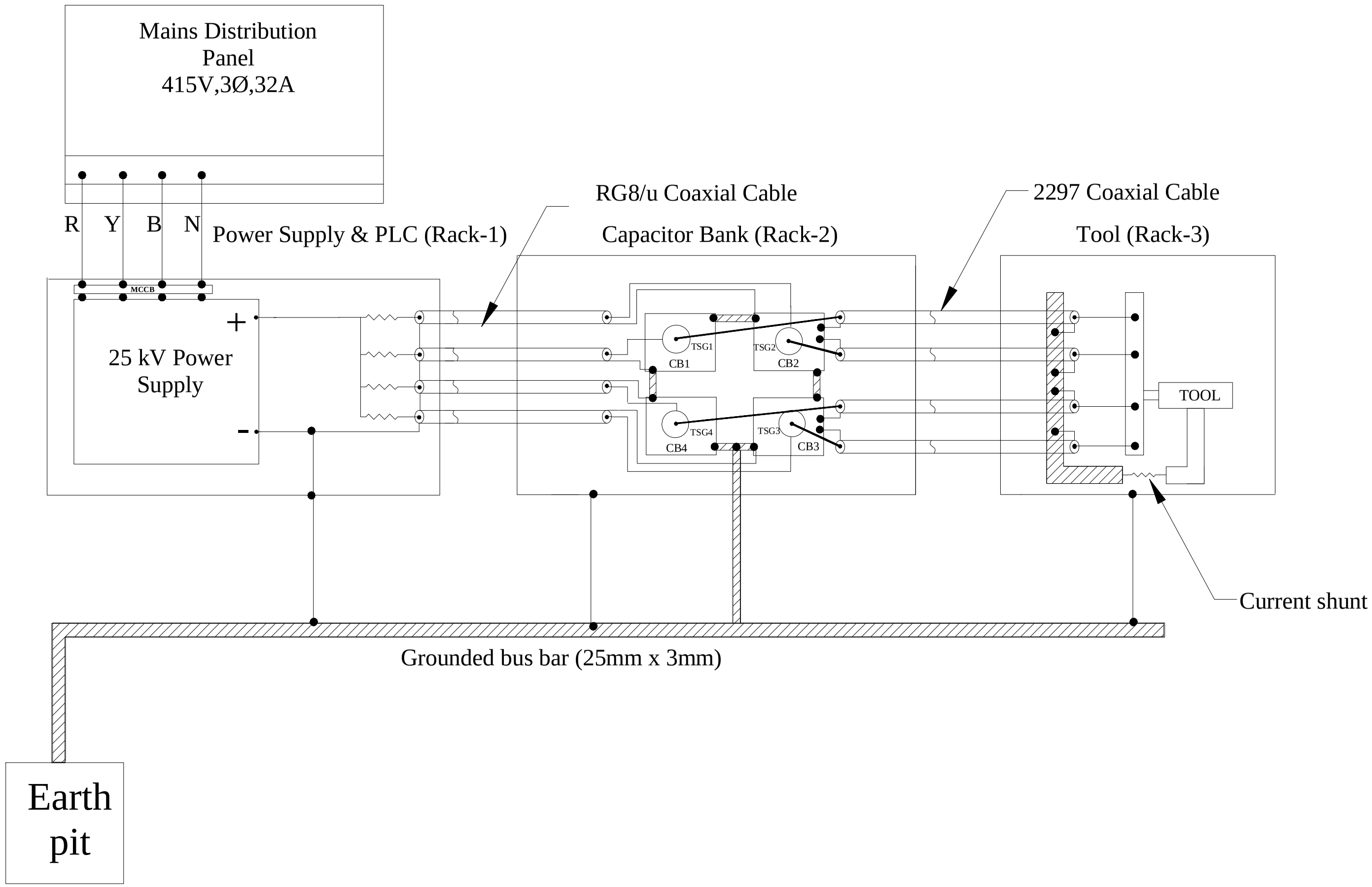


Delrin Sleeve
8 Nos.

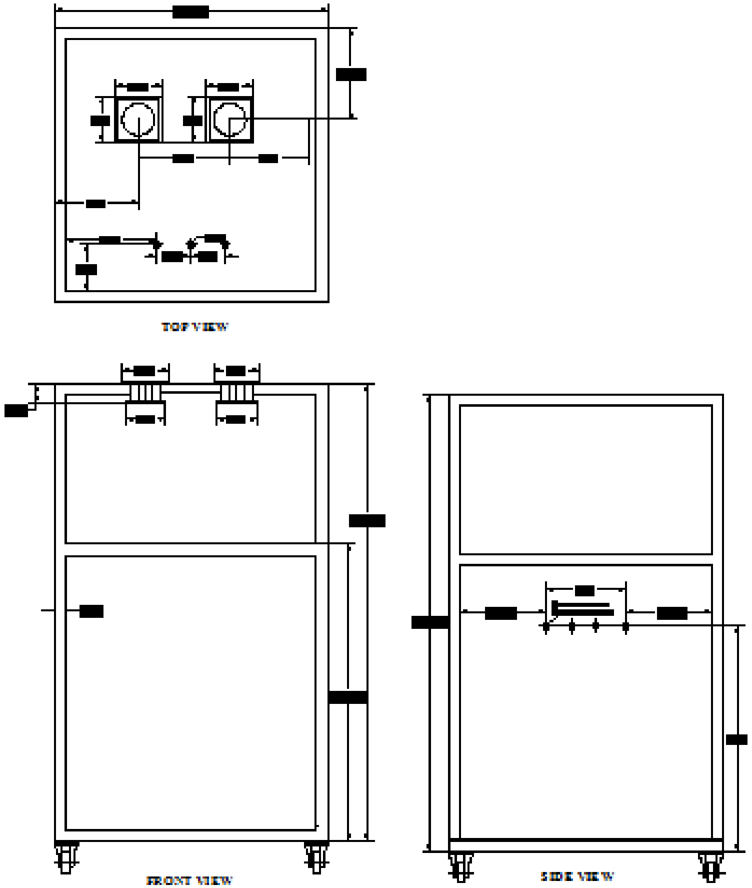


Delrin Sleeve
4 Nos.

C12: Coaxial discharge cable end component details



C13: Ground connection details



Sl.No.	Item Description	Quantity
1	Bayed EMC enclosure based on TS of dimensions 600W X 2000H X 1200D with ≥ 40 dB for magnetic field at 100kHz and ≥ 70 dB for electric field shielding up to 1 MHz	2
2	Castors 2 numbers with brakes and 2 numbers without brakes.	2
3	Side panels fixed screw type un vented for 2000H X 1200D (pack of 2).	1
4	Tube light 14W, 230V AC, 50 HZ with connection cable and micro switch	2
5	Door Operated switch with connection cable.	2
6	EMC Cable gland 2/ rack.	4
7	EMC Baying seal	2
8	17X23 Punched section (pack of 4).	2
9	Comfort handle.	2
10	Key insert.	2
11	EMC fan and Filter.	2
12	EMC Filter	2
13	System Support rails (pack of 2).	2
14	Quick fit baying clamps (pack of 6)	1
15	Angular Baying brackets	1

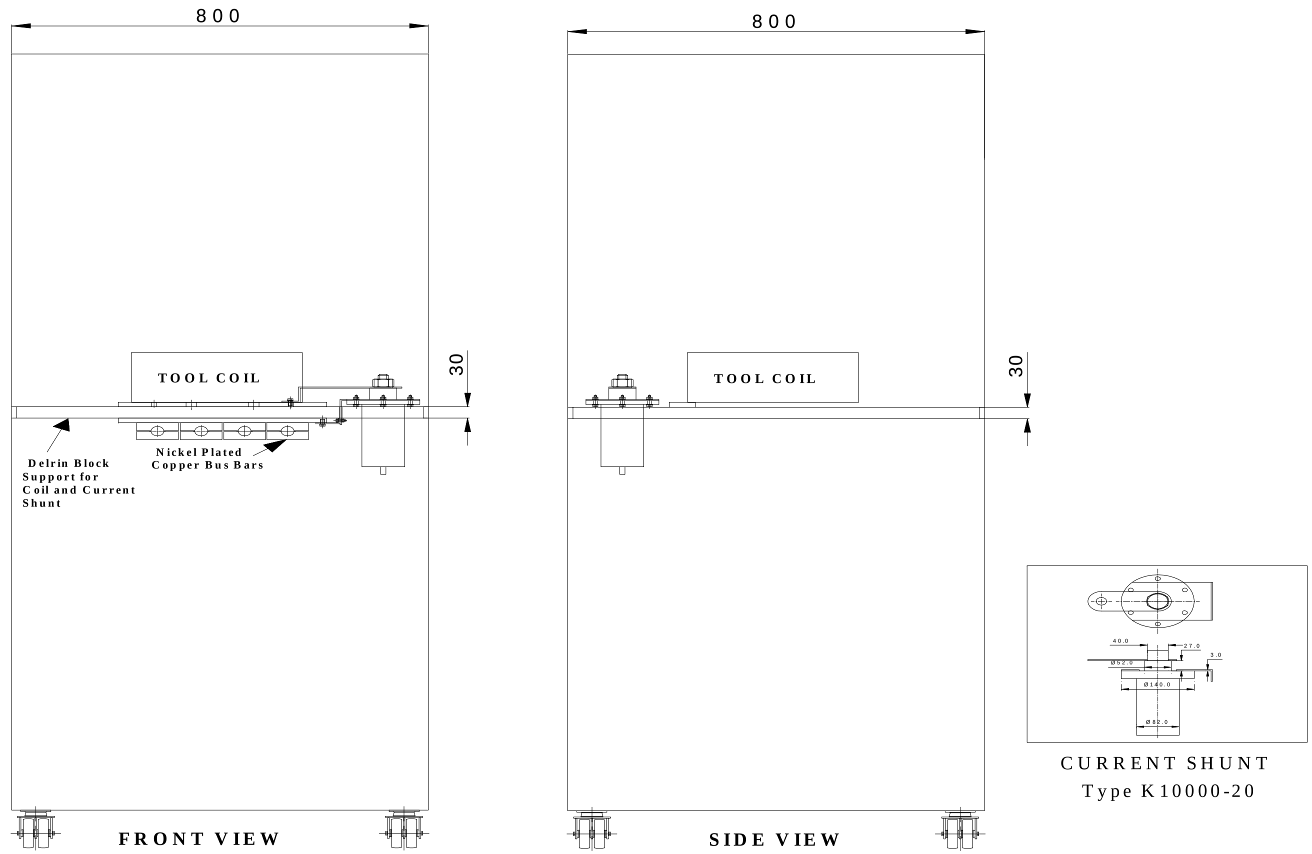
Additional Features & Accessories:

(i) EMI gasket to be provided at all mating surfaces.
(ii) Door: Double front and rear door with rod type locking facility
(iii) Protection class: IP-54
(iv) Bottom Supports: To be provided with heavy duty castor wheels with locking facility. (Internal components weight of EMC rack is about 2 Ton & control rack is about 500kgs)
(vi) Lifting bolts: I-bolts capable of lifting the assembled unit.
(v) Cable manager 2 numbers of 1U size (in top and middle compartments) and Cable channels 1 inch x 1 inch, on 2 sides for entire height and top across the width.
(vi) 50 Nos. Captive mounting hardware.
(vii)Cutout for cable entry(Location will be decided at the time of fabrication)

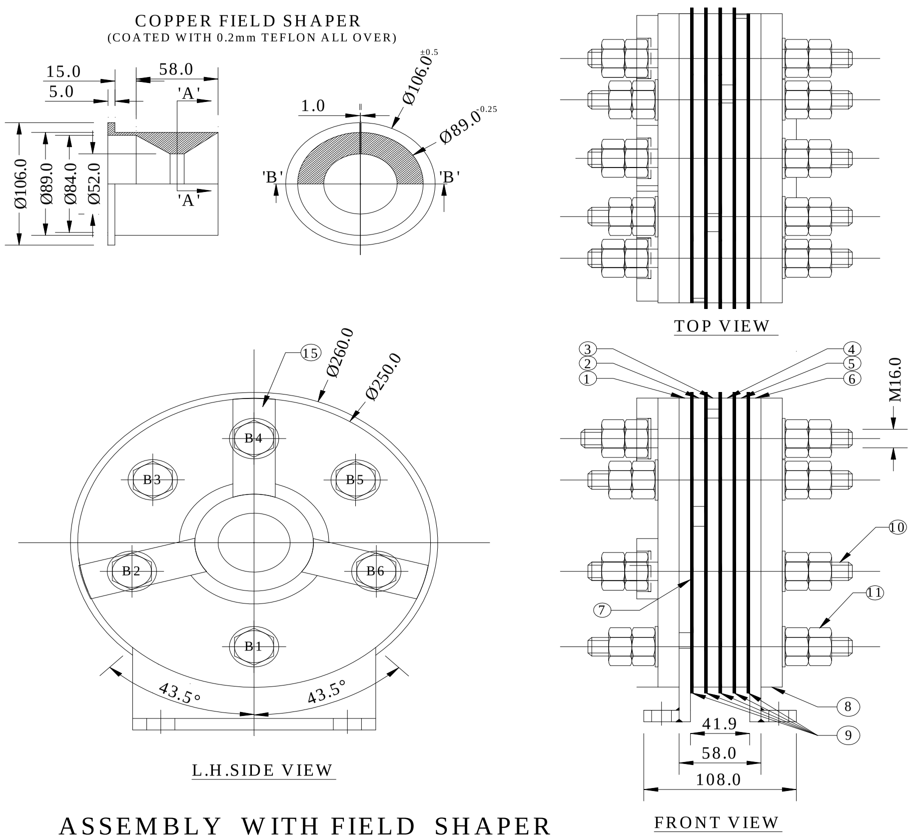
C14: Rack-2 Frame Details

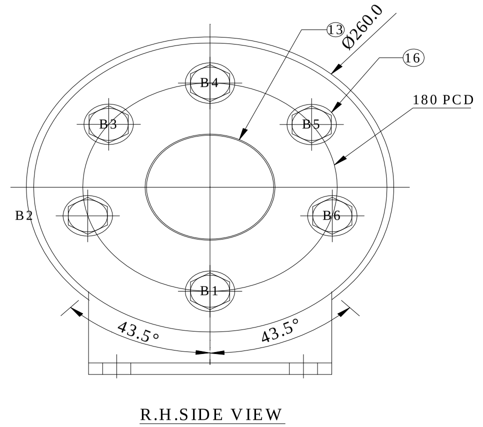
Appendix-D

Assembly, layout drawings in Rack-3



D1: ASSEMBLY LAYOUT OF EMM TOOL AND CURRENT SHUNT IN RACK-3

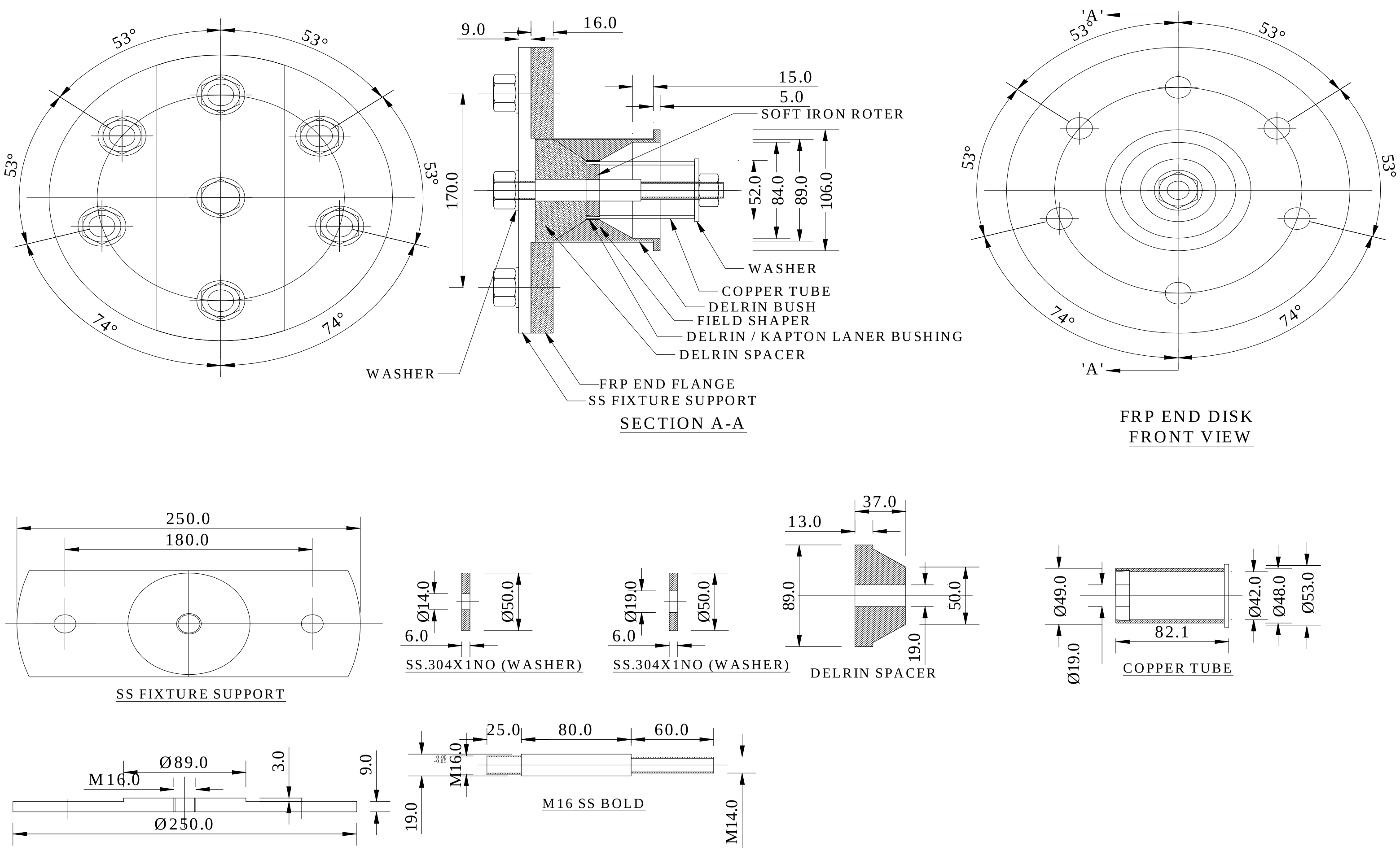




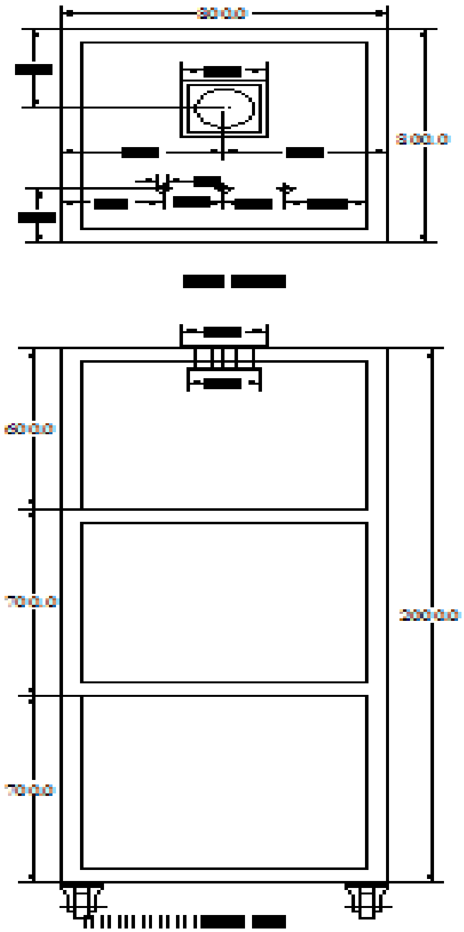
PART No	DESCRIPTION	MATL	QTY	REMARK
1	DISK NO.1	AL2024	1No.	
2	DISK NO.2	AL2024	1No.	
3	DISK NO.3	AL2024	1No.	
4	DISK NO.4	AL2024	1No.	
5	DISK NO.5	AL2024	1No.	
6	DISK NO.6	AL2024	1No.	
7	SECTORS	COPPER	5Nos.	
8	INSULATION END DISK	FRP END FLANGES	2Nos.	
9	INTER DISK INSULATION	FRP LAMINATED WITH 3MIL THK MYLAR BOTH SIDES	5Nos.	
10	STUD	SS304	6Nos.	
11	M16 HEX HD NUT	SS304	24Nos.	
12	STUD LINER	DELRYN	6Nos.	
13	FIELD SHAPER OD LINER	DELRYN	1No.	
14	FIELD SHAPER	COPPER	1No.	
15	FIELD SHAPER HOLDERS	FRP	3Nos.	
16	WASHER	SS304	12Nos.	

ASSEMBLY WITH FIELD SHAPER

D2: EMM TOOL & FIELD SHAPER DETAILS



D3: EMM TOOL FIELD SHAPER, FIXTURE & SAMPLE JOB DETAILS



Sl.No.	Item Description	Quantity
1	Non EMC enclosure based on TS of dimensions 800W X 2000H X 800D	1
2	Castors 2 numbers with brakes and 2 numbers without brakes.	1 set
3	Side panels fixed screw type un vented for 2000H X 800D (pack of 2).	1
4	Tube light 14W, 230V AC, 50 HZ with connection cable and micro switch	1
5	Door Operated switch with connection cable.	1
6	Cable gland	2
7	17 x 23 Punched section (pack of 4).	1
8	Comfort handle.	1
9	Key insert.	1
10	Fan and Filter.	1
11	Filter	1
12	System Support rails (pack of 2).	1
13	Mounting base plate and partition plate	1 set

Additional Features & Accessories:

(i) Gasket to be provided at all mating surfaces.
(ii) Door: Double front and rear door with rod type locking facility
(iii) Protection class: IP-54
(iv) Bottom Supports: To be provided with heavy duty castor wheels with locking facility. (Internal components weight of the rack is about 100kgs)
(vi) Lifting bolts: I-bolts capable of lifting the assembled unit.
(v) Cable manager 2 numbers of 1U size (in top and middle compartments) and Cable channels 1inch x 1 inch, on 2 sides for entire height and top across the width.
(vi) 50 Nos. Captive mounting hardware.
(vii) Cutout for cable entry

D4: Rack-3 Frame Detail

APPENDIX - E

List of Manufacturers/ Suppliers/ Fabricators of Major Components

(1) M/s NEO POWER ELECTRONICS & PROJECT PRIVATE LIMITED
216/221, P. N. KOTHARI INDUSTRIAL ESTATE,
LBS MARG, BHANDUP (W), MUMBAI- 400 078

(2) M/s KIRAN ELECTROMECH SYSTEM
36, VIRAWANI IND ESTATE
WESTERN EXPRESS HIGH WAY
GOREGOAN (E). MUMBAI-400 063

(3) M/s HI – TECH ENGG. SERVICES,
8, ARADHANA, BEHIND MODEL ENGLISH SCHOOL,
PANDURANGA WADI,
DOMBIVALI (E), THANE – 421201

(4) M/s NILKANTH FABRICATORS PVT LTD.
301, AMRUT PORBUNDARWALA COMPLEX
S.N.ROAD, MULUND (W)

(5) M/s RESHMA ENGINEERINGAWORKS,
BUSSA IND ESTATE, SEWREE.

(6) M /s. ACTIVE DEVICES INC.
KANYAKUMARI BUILDING, B/53,
5TH FLOOR, SIR. M.V. ROAD,
ANDHERI- EAST, MUMBAI- 400069

(7) M/s ZEONICS DEFENCE AND AEROSPACE ENGINEERS
NO. 236/2/2 MARUTHI NAGAR, 10TH MAIN,
OPP. 6TH CROSS, MALLESH PLAYA,
NEW THIPPASANDRA P.O BANGALORE-560 075

(8) M/s MAGNEWIN MAGNETICS
L-49, MIDC, KUPWAD,
SANGLI 416 436
MAHARASHTRA

(9) M/s GUJARAT MULCO ELECTRONICS LTD.
PLOT: A1/251/2, GIDC ESTATE
UMARGAM- 396 171
DIST.: VALSAD (GUJRAT), INDIA

(10) M/s YESHA ELECTRICALS PVT. LTD.
C-2/18, INDUSTRIAL ESTATE, GORWA ROAD
BARODA 390016. INDIA.

(11) M/s SIMPLEX RADIO ELECTRIC CARPORATION
6, BEST PRESS BUILDING, 100/112, MORLAND ROAD, MUMBAI-400 008.

(12) Ms ENGLISH ELECTRIC VALVE COM LIMITED.
WATERHOUSE LANE, CHEMLMSFORD, ESSEX CM1 2QU.

(13) M/s ITT JENNINGS, USA.
INTERNATIONAL TELEPHONE 7 TELEGRAPH CORPORATION.
770 MCLAUGHLIN AVENUE. SAN JOSE, CALIFORNIA 95122

(14) M/s INTERCON, 163, PANDURANG NAIK ROAD,
MAHIM, MUMBAI-400 016, INDIA.

(15) M/s INDUSTRIAL ELECTRICAL & ENGINEERING CORPORATION,
53, SHAH IND ESTATE, DEONAR. MUMBAI.

(16) M/s POWERTHERM CAPACITORS (I) PVT LTD.
A/16, GUL MAHAL, 10-SEAATER ROAD.
GRANT ROAD (W). MUMBAI-400 007

(17) NEXTGEN ELECTRICAL AND CABLE CO.
VIP ENCLAVE. VIP ROAD. BLOCK NO- A1.
SHOP NO.12 &13. KOLKATA-700 059

(18) M/s AQUA DE-ION ENGINEERS, B/15, SANYOGITA APARTMENT, ANAND NAGAR,
PANDIT DEEN DAYAL, ROAD, DOMBIVALI (WEST) - 421202.

(19) M/s ONUS ENGINEERING, D-36, NANDANVAN COMPLEX, PLOT NO. 125-A/7,
MUMBAI-PUNE HIGHWAY, PANVEL, PIN- 410206.

(20) MANAGER (IT SOLUTIONS) WEST, M/S RITTAL INDIA PVT. LTD. LEVEL 1, WING “A”,
L.B.S. MARG, VIKROLI (W), MUMBAI-400060. FAX NO. 91 22 25771733.

(21) M/S TECNIX EUROPAC, 6/8, RVE EUGENE DUPUIS 94000, CRETEIL, FRANCE

Annexure-1

0-25kV, 200mA High voltage resonant charging power supply specifications

Input	3 Phase, 415 V +/- 10%, AC,50 Hz
Output	0-25 kV, 0-200 mA, 5 kW
Display	4.5” Digital Panel Meter
Polarity	Negative
Size	Suitable for 19’’ (inch) rack
Output Connectors	Mating Connectors with 10 ft long high voltage cable
Input Connection	IEC 320 input connector, 6 ft long line cable
Chasis Ground	2 pin terminal block load return
Weight	< 50 kg
Front Panel Controls	Voltage (0-25 kV DC) Current (0-200 mA)
Indicator	On/Off circuit breaker lamp, High Voltage ON switch Indicator and High Voltage OFF switch Indicator
Cooling	Air cooling
Current Regulation	0.05% of max current
Efficiency	Equal to of More than 90% on full load
Protections	Against Short Circuits, HV Arc to ground, Mains over and under voltage, over temperature shutdown
Voltage Reversal	Upto 80% for a ringing freq. of 8-20 kHz
Power Factor	>0.98
Remote Operation	16 or 26 pin terminal block for remote control monitoring
Power supply common	Signal ground
Interlock Monitor	0V open, +15V closed
Fault Monitor	0V Fault, +15V No Fault
External Interlock Return	Return for Interlock
Current Monitor	0-10V = 0 to 100% rated output

Voltage Monitor	0-10V = 0 to 100% rated output
+10 V DC reference	+1kV DC, 5 mA max.
Remote current program In	0-10V = 0 to 100% rated output
Local current program Out	Front panel program voltage
Remote voltage program In	0-10V = 0 to 100% rated output
Local voltage program Out	Front panel program voltage
Power Monitor	0-10V = 0 to 100% rated output
Remote power program In	Optional
Local HV off Out	+15V at open, < 25mA at closed, connect to HV off for FP operation
HV off	connect to HV off for FP operation
Remote HV on	+15V, 10 mA max = HV off
Remote HV off Indicator	0= HV on, +15V,10 mA max =HV off
Remote HV on Indicator	0= HV off, +15V,10 mA max =HV on
Remote voltage mode	Open Collector 35 V max. 10mA max On = Archive
Remote current mode	
Remote power mode	
Remote PS fault	0= fault, +15V, 0.1 mA max = No fault
+15 V output	+15 V, 100 mA max.
Shield return	Chasis ground

Annexure-2

Vacuum contactor specifications

Sl.No.	Description of Parameters	Details of Parameters
1	Rated Voltage	50 kV Peak
2	Test Voltage	70 kV Peak
3	Rated continuous current	200A rms
4	Max. Interrupting Capability	400A rms
5	Contact Resistance	200μΩ
6	Contact Capacitance	5.5pF
7	Contact Inductance	45nH
8	Aux. Contact Voltage rating	230V AC rms
9	Aux. Contact Current Rating	15A rms
10	Aux. Contacts	SPDT
	Actuator Specifications	
a	Contacts Arrangements	NC
b	Actuator Voltage	230V AC rms
c	Pull in current	5.2 A rms
d	Hold Current	0.54A rms
e	Hold Power	18W
f	Closure Time	40 msec
g	Break time	70 msec

Annexure-3

Trigger transformer specifications

Sl. No.	Description of Parameters	Details of Parameters
1	Maximum DC input	600 VDC
2	Output voltage	30kV
3	Primary Turns	2
4	Secondary turns	75
5	Secondary Voltage rise time (typical)	100ns
6	Core	C Type Amorphous UMCC367 (M/s Hitachi Metglas)

Appendix-F

Bill of Materials in Rack-1

Sr. No	Item Description	Type No. / Technical Specification	Manufacturer	Nos.
1	EMC Enclosure Rack-1	Size: 800 mm W x 800 mm D x 2000 mm H (Diagram: B4)	M/s Rittal India Pvt. Ltd, Bengaluru	1
2	Charging Power Supply	25 kV/ 100mA Constant current type power Supply (Annexure -1)	M/s Technix, France	1
3	PLC	TWDLCAE40DRF Ethernet Port: 1 No. RS485 port: 1 No.	M/s Schneider	1
4	PLC Power Supply	Quint-PS-100-240VAC/24DC/5A	M/s Phoneix	1
5	AI/AO Module	TWDAMM6HT Digital Input: 16 Nos Digital Output: 24 Nos	M/s Schneider	2
6	Transient Suppressor Module	Model: SG770 Input channels : 7 Output Channels: 7 Maximum surge voltage: 6kV for 8/20 μs	M/s: ICPDAS	2
7	Isolator module	ADAM 3014 Isolation: 3 kV Input: mV to 10V Output: 0-10V	M/s Advantech, USA	10
8	HMI panel	XBTGT 2330 7 and 15 inches (one each) color touch screen with one Ethernet Port and one RS485 port	M/s Schneider	2
9	Control Panel	Size: 600mm W, 600mm D, 2000mm H	M/s Rittal India Pvt Ltd, Bengaluru	1
10	Dump switch	Model: RP900L Vacuum Contactor, 230V AC with NC contacts rated for 50kV, 200A rms (Annexure- 2)	(M/s HVITT Jennings)	1
11	Dump Resistor unit	Wire wound 25kΩ, 100W, 3 in series placed inside Polypropylene enclosure	M/s Kiyosh Electricals, Mumbai	1

Sr. No	Item Description	Type No. / Technical Specification	Manufacturer	Nos.
12	Power Supply Protection Circuit Components	Current limiting Resistor: 1 kΩ/100W (4 Nos) HV Diode: PIV :4kV (7 Nos) Snubber Capacitor: Ceramic 1kpF/3kV dc (7 Nos) Metal Film: Snubber resistors: 10Ω/1W HV arm divider resistor: Type: SOX124 500MΩ, 50 kV (4 Nos) LV arm resistor:250 kΩ (1MΩ, 4 in Parallel, 4 Nos. each) (Details in diagram: B5)	(M/s Kiyosh Electricals, Mumbai) Type HVRW4 (M/s HV Component Asso. USA) M/s Gujarat Mulco M/s EBG, Austria	1 set
13	Incoming Circuit breaker	MCCB, 125A, 3 Phase. 415V, 50Hz	M/s L&T/Siemens	1
14	Incoming Mains Cable	4 Core armored copper cable, (15A, 415V, 50Hz)	M/s Asian Cables	15
15	Fiber Optics Transmitter DC Power Supply Fiber Cable	Type HFBR1521Z SMPS Based,5 V, 1A Fixed type Fiber cable suitable for HFBR1521 transmitter and HFBR2521 receiver, 10 m length	M/s AVAGO Technologies M/s Aplab, Mumbai M/s Asha Sales, Mumbai	1 Set
16	HV Charging Cable	RG 8/U Coaxial HV Charging Cable suitable for 25 kV dc applications or Type2297, 50kV dc co axial cable	M/s Asian Cables, Mumbai/ M/s Nexgen, Kolkata	25 mtrs
17	Isolation transformer	400VA, 230V:230V with 2.5kV DC Isolation and CMRR:130dB	(M/s APLAB, Thane)	1
18	Miscellaneous	Lugs, Cable Tray, Cable channels, Ties, ferrules, Arma sound etc.		

Bill of Materials in Rack-2

Sr. No.	Item Description	Type No. / Technical Specification	Manufacturer	Nos.
1	Bayed EMC Enclosure	Size: 800 mm W x 1200 mm D x 2000 mm H (Diagram C12)	M/s Rittal India Pvt Ltd, Bengaluru	2
2	Energy Storage capacitors	14 µF/20 kV , ESL:100nH max. (Diagram C2)	M/s Yesha Electricals Baroda	16
3	High Current strip line Connectors	Nickel Plated Copper bus bars (Diagram: C3)	Fabrication item	1 Set
4	Trigger generator	(Diagram:C4)	Fabrication item	1 Set
5	Fiber optics Receiver DC Power Supply DC Bus Power Supply	Type HFBR2521 SMPS 5 V, 1A 600V DC, 1A (Diagram C4)	M/s AVAGO Technologies M/s Phoneix, Mumbai Fabrication item	1 Set
6	IGBT	Type: SKM800GA176D 1700V, 800A	M/s Semikron	1
7	Trigger Pulse Transformer	Details in Annexure -3 (Diagram C5)	Fabrication item	4
8	Spark Gap Switch	Coulomb Rating-1.5C, Self Breakdown setting: 22 kV, Interelectrode gap:8.5 mm, Trigger Pulse (9kV min, 400ns pulse width) (Diagram C6 and C7)	Fabrication item	4
9	Coaxial Chamber for Spark gap	Aluminum Chamber with polished surface (Diagram C8)	Fabrication item	4
10	Strip Line HV insulator	Polypropylene insulating Sheets Diagram C9	Fabrication item	1 Set
11	Metallic Ground Plate	Aluminum Ground plate (Diagram C3)	Fabrication item	01
12	Coaxial discharge cable Connector Plate Cable Glands Sleeves	Type:2297 50kV, 50A Co-axial Cable Nickel Plated Copper Plates EMC Glands, 32mm ID Delrin Sleeves (Diagram C13)	M/s Nexgen, Kolkata Fabrication item M/s Rittal India, Bengaluru Fabrication item	50 mtrs 16 Nos 8 Nos 12 Nos

Bill of Materials in Rack-3

Sr. No.	Item Description	Type No./ Technical Specification	Manufacturers	Nos.
1	Non EMC Enclosure	Size: 800 mm W x 800 mm D x 2000 mm H (Diagram D4)	M/s Rittal India Pvt Ltd, Bengaluru	1
2	Self Reinforced Disc Type Coil Field Shaper	No of turns: 5 Inductance:1.4µH Operating Voltage: 20kV, OD: 250mm, ID:90mm (Diagram D2) ID: 50mm, Length at ID:10mm (Diagram D3)	Fabrication item Fabrication item	1 Set
3	Job Fixture	To hold jobs of Copper tube and Soft iron disc in High field zone during joining process (Diagram D3)	Fabrication item	1
4	Support for Coil and Current Shunt	Delrin Block, Size: 780mm X 700 mm X 30mm (Diagram D1)	Fabrication item	1
5	Nickel Plated Copper Bus Bars	Nickel Plated Copper Busbar Size: 12mm X 50mm X 450mm (for establishing high current connections) (Diagram D1)	Fabrication item	4
6	Bolts and Nuts with washers	SS , M12 X 100mm long	Standard item	4

Appendix-G

List of Measuring Instruments

Sr. No.	**Item Description**	**Type No./ Technical Specification**	**Manufacturers**	**Nos.**
1	Current Shunt	Type: K10000-20 0.0005151Ω, 150W	M/s T&M Research Products	1
2	HV Probe	Type: P6015A 20kV DC, 40 kV Pulse, BW:75 MHz , Ratio: 1000X	M/s Tektronix	2
4	LCR Bridge	Type:4263B Max. Frequency: 100kHz, Variable frequency settings.	M/s Agilent Technologies	1
5	Digital Multimeter,	Type: MECO 2727	M/s MECO, Mumbai	1
6	RF Coaxial Cable	RG58/u with BNC connectors, 5 metres Length	M/s Asian Cables, M/s Times, USA	2
7	DSO	Type DSO1024, BW: 200MHz, Sampling Rate: 2GS/s	M/s Agilent Technologies	1
8	Attenuators and terminators	Attenuators: 3X Terminators: 50Ω	M/s Tektronix/ M/s Wave tek	5 each