Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

MINISTERO DELLO SVILUPPO ECONOMICO

Ingegnerizzazione di 8 sistemi di alimentazione elettrica per l'esperimento internazionale JT-60SA

P. Zito, P. Costa, A. Lampasi, G. Maffia, F. Starace

Report RdS/2013/188

INGEGNERIZZAZIONE DI 8 SISTEMI DI ALIMENTAZIONE ELETTRICA

PER L'ESPERIMENTO INTERNAZIONALE JT-60SA

P. Zito, P. Costa, A. Lampasi, G. Maffia, F. Starace (ENEA)

Settembre 2013

Report Ricerca di Sistema Elettrico

Accordo di Programma Ministero dello Sviluppo Economico - ENEA
Piano Annuale di Realizzazione 2012
Area: Produzione di energia elettrica e protezione dell'ambiente
Progetto: Attività di fisica della fusione complementari a ITER
Obiettivo: A.4 – Realizzazione di parte degli alimentatori dei magneti poloidali di JT-60SA
Responsabile del Progetto: Ing. Aldo Pizzuto, ENEA

Si desidera ringraziare il personale della POSEICO e della JEMA in RTI ed in particolare l'ing. M. Portesine e l'ing. F. Fasce per la collaborazione nella realizzazione del documento.

Indice

Sommario

Nell'ambito del Broader Approach (che è un accordo di cooperazione internazionale tra Unione Europea Euratom e Giappone avente lo scopo di integrare il progetto ITER ed accelerare i tempi per la realizzazione dell'energia da fusione, attraverso attività di R&S relative a tecnologie avanzate per i futuri reattori dimostrativi), l'ENEA deve fornire parte delle alimentazioni elettriche del sistema magnetico di JT-60SA, per un totale di 8 alimentatori ad alta corrente (6 alimentatori per le bobine poloidali CS1, CS2, CS3, CS4, EF1 e EF6, 2 alimentatori per le bobine FPPC Fast Plasma Position Control con relativi interruttori e trasformatori).
L'ENEA ha condotto gli studi e la progettazione per la realizzazione di alimentatori AC/DC e relativi trasformatori, per gli avvolgimenti poloidali e di controllo della macchina JT60SA. Le alimentazioni elettriche degli avvolgimenti devono fornire una corrente continua regolabile in grado di riprodurre gli scenari di corrente desiderati. Gli scenari di corrente di un tokamak prevedono una prima fase caratterizzata da una lenta salita (ramp-up) della corrente prodotta dal convertitore a tiristori, fino a un massimo valore prestabilito (20 kA nel caso dei CS). Le specifiche tecniche elaborate definiscono i parametri funzionali del sistema, la modalità di funzionamento e i limiti di esercizio.
Il contratto per la fornitura di otto Alimentatori e sei Trasformatori per JT- 60SA PFC PS (CS1 , CS2 , CS3 , CS4 , EF1 e EF6 PS e le due FPPC PS) è stato assegnato da ENEA al fornitore industriale POSEICO - JEMA in RTI il 01/agosto/2013.
Il contratto di appalto è basato su specifiche tecniche e di gestione della qualità sviluppate da ENEA con la stretta collaborazione di F4E e JAEA. Le caratteristiche del sistema e i documenti di specifica tecnica e di gestione della qualità sono stati accuratamente analizzati e discussi, durante il kick-off meeting e i successivi. In quell'occasione POSEICO - JEMA presentarono il piano di gestione della qualità e l'organigramma completo con l'indicazione del responsabile tecnico e il responsabile della qualità.
La progettazione è basata su criteri di conformità ai requisiti, modularità, affidabilità, manutenibilità, mitigazione del rischio e analisi dei guasti. Gli aspetti specifici del progetto sono stati definiti durante la fase 1 di progettazione di dettaglio discussa nei meeting successivi, che prevede come risultato finale:

- **1.a. il dimensionamento esecutivo dei trasformatori;**
- **1.b. la redazione del documento relativo all'ingegnerizzazione con selezione della componentistica industriale dei sistemi di alimentazione.**

Il presente documento riporta il dimensionamento esecutivo dei trasformatori e la redazione del documento relativo all'ingegnerizzazione con selezione della componentistica industriale dei sistemi di alimentazione. Inoltre, poiché tutta la documentazione fornita è in lingua inglese, i prossimi paragrafi sono riportati in inglese.

1 Introduzione

The power supply system consists of the power supplies for the superconducting and control coils, the beam and EC heating and current drive systems, and power supplies for auxiliary plant. Existing equipment is re-used where possible, on a rearranged AC supply network. New power supply systems will be designed and manufactured to feed the superconducting TF and PF coils.
In this context, ENEA shall provide 8 new Power Supplies and 6 new transformers for part of the JT-60SA PFC PSs (including the “Central Solenoids” CS1, CS2, CS3, CS4, “Equilibrium Field” EF1 and EF6 PSs) and the “Fast Position Plasma Control” FPPC PSs.
The PF coil power supplies shall provide a bipolar DC current adequate to achieve the required scenarios on the CS and EF superconducting coils. The two FPPC coils, the first in an upper position the second one in a lower position with respect to the vacuum chamber of JT-60SA, will be used to control plasma position. FPPC PSs shall provide the current needed to produce magnetic field on the plasma to control its position. The basic circuit components are a "Base PS", a "Booster PS", and an "SNU". Each CS and EF coil power supply has an independent DC circuit configuration. Corresponding to plasma operation with polarity reversal of toroidal magnetic field, current reversing links will be provided for all CS and EF coil power supplies. The reason of asymmetric current rating (-20kA to +10kA) in Base PS for EF1, EF2, EF5, and EF6 comes from the expected operational space.
The power supplies for upper/lower fast plasma position control coils (copper) have the function of control vertical and horizontal position of the plasma against small plasma perturbations such as a minor disruption. To maximize the control range with small cross section of the lower and upper fast plasma position control coils, a four quadrant operating thyristor converter is required with a minimum delay time. The maximum induced coil current in case of plasma disruption is estimated to be ~21 kA (in the case of 23 turn coils). In this case the PS crowbar operation has to be envisaged, also because high impedance of the PS may cause overvoltage in the coil.
The Contract for the Procurement of 8 new Power Supplies and 6 new transformers for part of the JT-60SA PFC PSs was awarded by ENEA to a Temporary Grouping of Companies (TGCs) in July 2013 composed by POSEICO and JEMA. The TGCs has a wide experience in the field of power electronics applied to nuclear fusion and is already involved in several international projects.
Important dates and milestones:

1. Call for Tender launched in April 2013;
2. Selection of Industrial Supplier carried out in June 2013;
3. Contract signed and start of activities in August 2013;
4. First Design Report in Autumn 2013;

Both POSEICO and JEMA have great experiences in the fields of power electronics and of power supplies. The former focuses its experience on semiconductor devices (diode, thyristor GTO, and IGBT) cooling systems (innovative and integrated heat-sink) and static converters (rectifier and inverters mainly for railway system and electric traction). The latter focuses its experience on high precision and high current power supplies for nuclear physics and nuclear fusion and it is already involved in several international projects, such as: MAST, JET, JT60SA (CEA Contract) and STELLERATOR.
The procurement technical and management activities started immediately after the award of the contract. The Kick Off Meeting was held at the ENEA Research Centre in Frascati, Italy, on 01 August 2013. The procurement is based on technical specifications developed by ENEA with the close collaboration of F4E and JAEA. During the Kick Off Meeting, the system characteristics and the technical and quality & management specification documents were thoroughly analyzed and discussed. POSEICO - JEMA presented the main management and quality plans. Also a complete organigram was presented identifying the technical responsible officer and the quality responsible officer. Furthermore, POSEICO-JEMA presented how the contractual phases and sub-phases of the project were split between POSEICO and JEMA, and a preliminary schedule for implementation of the project was shown, identifying main deadlines and milestones (in autumn 2013 will be issued the Transformers and First Design Report, in 2014 the FPPC power supplies, in 2016 CSs and EFs power supplies and the delivery to Japan is expected in 2017).

The POSEICO-JEMA PS Design will be based on criteria of conformity to requirements, modularity, reliability, maintainability, risk mitigation and fault analysis. The specific aspects of the project will be defined during the detailed design phase that will be deeply discussed in next progress meetings. These documents shall define the characteristics of main components and devices of the procurement, thyristors, power stack assembly and general layout complying to the technical a quality ENEA technical specifications. This document is based on the first draft of Design Reports provided by POSEICO-JEMA.

2 Il dimensionamento esecutivo dei trasformatori

2.1 Scope

The scope of this section is to provide all information necessary for the activities of report of the following transformers specifications and design

n°2 27136 KVA, oil type transformers for CS2, CS3 Power supply;

n°4 5220 kVA, dry type transformers for FPPC lower and FPPC upper Power Supply.

2.2 JT60SA PS requirements for transformers

2.2.1 CS2 and CS3 transformer requirements

New transformers are required for CS2 and CS3 PSs. The main characteristics foreseen for these transformers are summarized in Table 1. In according to technical specification, the IS can propose a design solution different from the reference one. In this case, the IS shall prove the convenience of the alternative solution proposed which shall be evaluated and approved by the Customer before to be adopted. In any case, the transformers have to comply with IEC 60076 and IEC 61378 for design, construction and tests. In particular, the following points have to be noticed:

- A single electrostatic screen shall be located between primary and secondary windings of the transformer. This has the double scope to reduce stray capacitance and to prevent any contact between the windings in case of insulation failure. For this reason, the screen has to be grounded.
- Transformer case shall be protected against possible oil overpressure with suitable apparatus to prevent any risk for the operators and the other nearby apparatus. The IS shall demonstrate it during DDP.
- HV and LV transformer connections shall be protected with a IP52DH enclosure.
- The noise limits are given by builder.
- Taking into account that the transformer could be transported by sea, in this case, all external components shall be properly painted/arranged in order to withstand sea environmental conditions without problem. The IS shall demonstrate it during the DDP.

At least, each transformer shall have the follow protective/monitoring devices:

- Over current versus time relay;
- Thermal relay;
- Buchholz relay;
- Temperature monitor (indicate temperature in the transformer’s topmost oil layer with maximum and minimum signal contacts);
- Oil level alarms;
- Oil flow indicator (in the case of forced oil circulation);
- Air flow indicators (only for fan cooled transformers).

The transformers shall include phase voltage transducers at the primary side in order to provide signals for synchronization of thyristor gates but also for measurement and protection purposes.

Table 1 - Reference design characteristics for the CS2 and CS3 new transformers.

Transformer characteristic	Value
Type	Three windings
Winding electrical connections	Ddy11
RMS current at each secondary winding	8.16 (kA)
Voltage ratio	18 kV / 0.96 kV
Z at 77.6 Hz (to be confirmed during the DDP)	24%
$Z_{12,13}$ at 77.6 Hz	To be determined by IS
Z_{23}	Magnetically decoupled
Frequency operating range	54.2-77.6 Hz
Rated withstand voltage (factory test voltage to ground) at primary side	50 kV RMS/50Hz/1m
Rated withstand voltage (factory test voltage to ground) at secondary side (IEC 60076-3 voltage 7.2 kV due to 5 kV voltage during QPC/SNU operation)	20 kV RMS/50Hz/1m
Rated lightning impulse withstand voltage on primary side	125 kV peak
Rated lightning impulse withstand voltage on secondary side	Not applicable
Voltage class	IEC 60076-3
Duty cycle	220/1800 (s/s)

2.2.2 FPPC Transformers requirements

New transformers are required for the FPPC PSs with the main characteristics listed in Table 2. The IS can propose a design solution different from the reference one. Moreover, in this case, the IS shall prove the convenience of the alternative solution proposed which shall be evaluated and approved by the Customer before to be adopted. In any case the transformers have to be complying with IEC 60076 and IEC 61378 for design, construction and tests. In particular the following items have to be noticed:

- A single electrostatic screen shall be located between primary and secondary windings of the transformer. This has the double scope to reduce stray capacitance and to prevent any contact between the windings in case of insulation failure. For this reason, the screen has to be grounded.
- In case of oil insulated transformer, the transformer case shall be protected against possible oil overpressure with suitable apparatus to prevent any risk for the operators and the other nearby apparatus. The IS shall demonstrate it during DDP.
- HV and LV transformer connections shall be protected with a IP52DH enclosure.
- Audible noise shall be limits indicated.
- Taking into account that the transformer could be transported by sea, its case and all external components shall be properly painted/arranged in order to withstand sea environmental conditions without problem. The IS shall demonstrate it during the DDP.

At least, each transformer shall have the same protective/monitoring devices required for the CS2 and CS3 transformers.

The transformers shall include phase voltage transducers at the primary side in order to provide signals for synchronization of thyristor gates but also for measurement and protection purposes.

Table 2 - Reference design characteristics for the FPPC transformers.

Transformer characteristic and parameter	Value
Type	Three windings
Winding electrical connections	Ddy11
RMS current at each secondary winding	4 kA
Voltage ratio	18/0.39 kV/kV
Nominal power	2.61 MVA
Z at 77.6 Hz (to be confirmed during the DDP)	20%
$Z_{12,13}$ at 77.6 Hz	To be determined by IS
Z_{23}	Magnetically decoupled
Frequency operating range	54.2-77.6 Hz
Rated withstand voltage (factory test voltage to ground) at primary side	50 kV RMS/50Hz/1m
Rated withstand voltage (factory test voltage to ground) at secondary side (IEC 60076-3 voltage 7.2 kV due to 5 kV voltage during QPC/SNU operation)	10 kV RMS/50Hz/1m
Rated lightning impulse withstand voltage on primary side (not applicable in case of indoor installation)	125 kV peak
Rated lightning impulse withstand voltage on secondary side	Not applicable
Voltage class	IEC 60076-3
Duty cycle	140/1800 (s/s)
Insulation medium (to be determined)	Oil/dry

2.2.3 Applicable Standards for transformers

The main international standards are reported as follows.

IEC 60076-11	**CEI EN 60076-11**	Trasformatori di potenza a secco
IEC 60076-1	**CEI EN 60076-1**	Trasformatori di potenza Parte 1: Generalità
IEC 60076-2	**CEI EN 60076-2**	Trasformatori di potenza Parte 2: Riscaldamento
IEC 60076-3	**CEI EN 60076-3**	Trasformatori di potenza Parte 3: Livelli di isolamento, prove dielettriche e distanze isolanti in aria
IEC 60076-5	**CEI EN 60076-5**	Trasformatori di potenza Parte 5: Capacità di tenuta al corto circuito
IEC 60076-10	**CEI EN 60076-10**	Trasformatori di potenza Parte 10: Determinazione dei livelli di rumore
IEC 61378-1		Transformers for industrial applications

2.2.4 Transformer Design Criteria

Main transformer design criteria are the following items:

- Conformity to Custom requirements;
- Optimization of magnetic circuit in order to reduce losses, weight and cost of magnetic materials.

2.3 *Transformer Technical Specifications*

2.3.1 Transformers Manufacturer

Both the transformer types are manufactured from SEA Spa Headquarters via Leonardo da Vinci 14, 36071 Tezze di Arzignano (VI) Italy.

2.3.2 CS2 and CS3 Transformers

In the next paragraphs are reported the Technical Description of CS and CS3 Transformers

2.3.3 Overview

Three phase double tie oil immersed converter transformer our designation type OTR, ONAN cooling for indoor or outdoor installation. Special design for a short time operation under a duty cycle specified by client, suitable to feed a 12 pulse converter.

The specified duty cycle is herewith described:

· Total duration of each cycle: 1800 sec

· Duration of operation at 100% of power: 220 sec

· Duration of operation at 0% of power: 1580 sec

· Operation under specified duty cycle: continuously

· Energization of transformer: continuously

2.3.4 Core of transformer

Magnetic core is made by cold rolled laminations, grain oriented hi-permeability type. The flux density is calculated not more than 1,55 T at 18 kV excitation voltage (the primary voltage) and 77,6 Hz, but transformer is designed to be operated at frequencies down to 54,7 Hz, assuming that excitation voltage is linearly reduced consequently in order to have a V/f=K, as common rule for all transformers (i.e. ratio becomes 12688/2x676,7V) Suitable core clamps (wooden or steel type) are designed avoiding bolts and holes in the laminations, in order to reduce as much as possible the losses, the noise and the vibrations. Suitable cooling ducts, if necessary, are provided to keep the thermal field uniform and free of hot points.

2.3.5 Windings

Transformer is a double ties type, that means two independent secondary coils are vertically stacked in each core leg and two sections of primary windings are parallel connected.

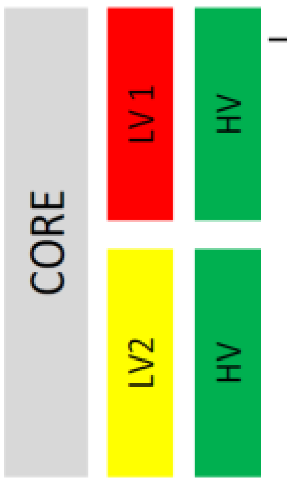


Fig. 1 – Configuration of windings of transformer (in grey the magnetic core, in green primary windings split in two parts and in red and yellow secondary e tertiary windings respectively).

One secondary winding is delta connected, the other one is star connected in order to obtain a connection suitable to realize 12 pulse reaction at line side. All windings are round, concentric type, made by hi-grade

electrolytic copper. Both LV windings are made by CTC (Continuously transposed cable) or foil. In particular, we will use the foil type only after a detailed evaluation of edge behaviour along entire range of frequencies, which will be done by FEM during detailed design HV windings are made by layers of copper strips insulated by pure cellulose paper. Windings are properly dried in autoclave before mounting in the core. The assembling of windings is carefully performed to avoid misalignment. Windings are properly braced by wooden clamping rings, to assure uniform distribution of compression forces.
Suitable axial cooling ducts are provided inside each winding, to assure the uniform temperature field and avoid hot spots. Calculation of eddy current distribution by FEM is performed in our technical dept. during detailed design stage.
The particular operation of this transformer suggest a very strong mechanical design of coils and relevant axial/radial bracing of coils, with detailed evaluation of forces and use of devices to assure the durability of all fixing torques, in particular the axial pressure on coils to avoid any loose during long type operation

2.3.6 MV and LV connections

All leads coming from windings are connected to suitable oil to air bushings located on the cover. Bushings are brown, porcelain type:

- 3x 24 kV / 1250A according to EN50180 at primary 18 kV side;
- 2x3 x 3,6 kV / 3150 A at secondary 2x960 V.

Please note that bushings at LV side are calculated considering the duty cycle of transformer. All bushings are protected by IP55 air filled cable boxes, made by suitable steel plates. Each cable box includes copper bus-bars (with relevant supports) and large nonmagnetic gland plate suitable to accommodate the number and size of cables that client will indicate at order stage.
Please note that cable glands and cable ends are not included in our scope of work, and glands plates will be delivered undrilled.

2.3.7 Tank, cover and conservator and cooling equipment

The tank is a conservator type, top bolted. Both tank and cover are made by welded steel sheets, reinforced by stiffeners. Set of 4 (four) flat wheels are provided and included in our scope of work.

2.3.8 Cooling

Assuming the particular operation of this unit, a detailed calculation of temperature rise of oil and windings will be performed at design stage. In particular, we will evaluate the behaviour of windings either during the short time operation as well as in the long (indefinite) time under specified duty cycle.
Oil temperature and consequent cooling surface (quantity and dimension of radiators) will be defined assuming an indefinite operation under specified duty cycle and ambient temperature according to IEC Standard (annual average 20°C - max 40°C). As usual, each radiator will be equipped with flanges with interception valves, draining plug, air releasing plug, earthing terminal, lifting lug.

2.3.9 Painting

All external ferrous parts including radiators are painted accordingly to SCV30 attached. Final shade RAL 7033.

2.3.10 Oil type

Transformer is filled by naphtenic non-inhibited type Transag 10GN.

2.3.11 Table of characteristics

In the following table 3 are reported the complete CS2 and CS3 transformer specifications. In the column 3 are reported the customer requirements:

Table 3 - Characteristics for the CS transformers.

	POSEICO transformers specification	*Customer requirements*
Type	Three windings	Three windings
Rating power:	27136 kVA	
Secondary 21/22 power rating:	13568 / 13568 kVA	
Service:	Special	
RMS current at each secondary winding	-	8.16 kA
N° of Phases:	3	
N° of Windings per phase:	3	
Cooling	ONAN	
Fn:	54,7 ÷ 77,6 Hz Suitable for operation at 77,6 Hz and lower to 54,2 Hz, assuming V/f=constant	54.2-77.6 Hz
No load primary voltage:	18 KV	18 KV
Number secondary windings:	2 (vertically stacked in theleg)	
No-load secondary voltage:	960 - 960 V	960 V
Vector group:	Dd0,y11	Ddy11
Insulating level at I°:	24 / 50 / 125 kV	Rated withstand voltage (factory test voltage to ground) at primary side 50 kV RMS/50Hz/1m
Insulating level at II°:	3,6 / 10 / -- / 3,6 / 10 / -- kV	Rated withstand voltage (factory test voltage to ground) at secondary side (IEC 60076-3 voltage 7.2 kV due to 5 kV voltage during QPC/SNU operation) 10 kV RMS/50Hz/1m
Insulating class I°/II°:	A / A	
Primary/Secondary winding conductors:	Cu / Cu	
Primary bushings protection degree:	IP55 (cable glands excluded)	
Secondary bushings protection degree:	IP55 (cable glands excluded)	
Ambient temperature [MIN / MAX]:	-25 / +40 °C	
Overtemp. Oil / Avv.:	60 / 65 °C	
Altitude of installation	≤1000 mt	
Installation:	Outdoor	
Po at 1 Vn:	6000 W	
Pcc at 75°C and Sn:	390000 W Short circuit losses are referred to 27136 kVA (short time ON power), sinusoidal wave	
Load losses	No load losses are referred to 77,6 Hz, rated voltage, but informative only	
Vcc at 75°C and Sn:	24%	
Voltage class	-	IEC 60076-3
Duty cycle	Duty cyle for operation: 220s ON / 1800s total indefinitely	220/1800 (s/s)
Z at 77.6 Hz (to be confirmed during the DDP)	24% at HV/LV1+LV2 - 27136/2x13568 kVA - 18000/960 + 960 V - 77,6 Hz	24%
$Z_{12,13}$ at 77.6 Hz	approx 22% at HV/LV1 or HV/LV2 - 13568 kVA - 77, 6 Hz	To be determined by IS
Z_{23}	approx 32-36% between LV1 and LV2 at 13568 kVA - 77,6	Magnetically decoupled
Lp(A) a 0.3mt :	72 dB(A)	
Painting / Colour:	ISO12944-C3 / RAL 7033 Fittings and	

	POSEICO transformers specification	*Customer requirements*
	accessories (valves, fans, OLTC, kiosk, relays etc) will remain with original painting shade	
Tank execution:	Flta tank reinforced	
Insulation Media	Oil Type Naftenic not inibited 10GN	Oil/dry
Transformer overall dimensions (LxWxH):	3500 x 2600 x 3700 mm	
Transformer weight	16500 kg	
Oil weight:	2500 kg	
Untanking weight	9000 Kg	
Rated lightning impulse withstand voltage on primary side **(not applicable in case of indoor installation)**	-	125 kV peak
Rated lightning impulse withstand voltage on secondary side	-	Not applicable
Voltage class	-	IEC 60076-3
Duty cycle	Duty cyle for operation: 220s ON / 1800s total indefinitely	220/1800 (s/s)
Accessories	Silica gel dryer for transformer	
	Oil level indicator for transformer, with contacts	Oil level alarms;
	Oil drain valve and lower valve for oil treatment	
	Top valve for oil treatment	
		Oil flow indicator (in the case of forced oil circulation);
		Air flow indicators (only for fan cooled transformers)
	Dial type oil thermometer with contacts	
	PT100 sensor for temperature oil detection	Temperature monitor (indicate temperature in the transformer's topmost oil layer with maximum and minimum signal contacts);
		Thermal relay;
	PT100 sensor for core temperature detection	
	Bi-directional wheels plane type	
	Buchholz relay contacts	Buchholz relay;
	Intercepting valves for Buchholz relay	
	Pressure relief valve with contact	
		Over current vs time relay;

2.3.12 FPPC Transformers

In the next paragraphs are reported the Technical Description of FPPC Transformers

2.3.13 Overview

Three phase double tie dry type converter transformer our designation type TTR-C, AN cooling for indoor installation.
Special design for a short time operation under a duty cycle specified by client, suitable to feed a 12 pulse converter.
The specified duty cycle is herewith described:
· Total duration of each cycle: 1800 sec
· Duration of operation at 100% of power: 140 sec
· Duration of operation at 0% of power: 1660 sec
· Operation under specified duty cycle: continuously
· Energization of transformer: continuously

2.3.14 Magnetic Core

Core is made by cold rolled laminations, grain oriented hi-permeability type. The flux density is calculated not more than 1,6 T at 18 kV excitation voltage (the primary voltage) and 77,6 Hz, but transformer is designed to be operated at frequencies down to 54,7 Hz, assuming that excitation voltage is linearly reduced consequently in order to have a V/f=K, as common rule for all transformers (i.e. ratio becomes 12688/2x275V). Suitable core clamps (galvanized steel type) are designed avoiding bolts and holes in the laminations, in order to reduce as much as possible the losses, the noise and the vibrations.
Suitable cooling ducts, if necessary, are provided to keep the thermal field uniform and free of hot points.

2.3.15 Windings

Transformer is a double ties type, that means two independent secondary coils are vertically stacked in each core leg and two sections of primary windings are parallel connected.

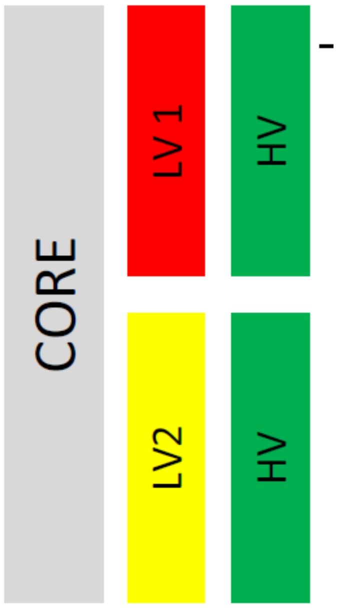


Fig. 2 – Configuration of windings of transformer (in grey the magnetic core, in green primary windings split in two parts and in red and yellow secondary e tertiary windings respectively).

One secondary winding is delta connected, the other one is star connected in order to obtain connection suitable to realize 12 pulse reaction at line side. All windings are round, concentric type, made by aluminium.

LV windings are impregnated, HV windings are casted under vacuum by epoxy. The assembling of windings is carefully performed to avoid misalignment. Calculation of eddy current distribution by FEM is performed in our technical dept. during detailed design stage.
The particular operation of this transformer suggest a very strong mechanical design of coils and relevant axial/radial bracing of coils, with detailed evaluation of forces and use of devices to assure the durability of all fixing torques, in particular the axial pressure on coils to avoid any loose during long type operation.

2.3.16 MV and LV connections

All leads coming from windings are available on transformer coils and/or structure, IP00 protected as usual for dry type transformers.

2.3.17 Cooling

Assuming the particular operation of this unit, a detailed calculation of temperature rise of oil and windings will be performed at design stage. In particular, we will evaluate the behaviour of windings either during the short time operation as well as in the long (indefinite) time under specified duty cycle.

2.3.18 Table of characteristics

In the following table 4 are reported the complete FPPC transformers specifications. In the column 3 are reported the customer requirements:

Table 4 - Characteristics for the FPPC transformers.

	POSEICO transformers specification	***Customer requirements***
Type	Three windings	Three windings
Rating power:	5220kVA	
Secondary 21/22 power rating:	2610 / 2610 kVA	
Service:	Special	
RMS current at each secondary winding	3.863 kA	4 kA
N° of Phases:	3	
N° of Windings per phase:	3	
Cooling	AN	
Fn:	54,7 ÷ 77,6 Hz Suitable for operation at 77,6 Hz and lower to 54,2 Hz, assuming V/f=constant	54.2-77.6 Hz
No load primary voltage:	18 KV	18 KV
Number secondary windings:	2 (vertically stacked in theleg)	
No-load secondary voltage:	390 V - 390 V	390 V
Vector group:	Dd0,y11	Ddy11
Insulating level at I°:	24 / 50 / 125 kV	Rated withstand voltage (factory test voltage to ground) at primary side 50 kV RMS/50Hz/1m
Insulating level at II°:	3,6 / 10 / --kV	Rated withstand voltage (factory test voltage to ground) at secondary side (IEC 60076-3 voltage 7.2 kV due to 5 kV voltage during QPC/SNU operation) 10 kV RMS/50Hz/1m
Insulating class I°/II°:	F / F	
Primary/Secondary winding conductors:	Cu / Cu	
Classes (ambient, cimate,fire)	E2-C2-F1	
Design max. ambiente temperature	40°C	
Overtemp. Prim/sec windings:	100 / 100 °C	
Altitude of installation	≤1000 mt	
Installation:	Indoor	
Transformer protection degree:	IP00	

	POSEICO transformers specification	*Customer requirements*
Po at 1 Vn:	6000 W	
Pcc at 75°C and Sn:	100000 W Short circuit losses are referred to 5220 kVA (short time ON power), sinusoidal wave	
Load losses	No load losses are referred to 77,6 Hz, rated voltage, but informative only	
Vcc at 75°C and Sn:	20%	
Voltage class	-	IEC 60076-3
Duty cycle	Duty cyle for operation: 140s ON / 1800s total indefinitely	140/1800 (s/s)
Z at 77.6 Hz (to be confirmed during the DDP)	20% at HV/LV1+LV2 - 27136/2x13568 kVA - 18000/960 + 960 V - 77,6 Hz	20%
$Z_{12,13}$ at 77.6 Hz	approx 18% at HV/LV1 or HV/LV2 - 13568 kVA - 77, 6 Hz	To be determined by IS
Z_{23}	approx 30-35% between LV1 and LV2 at 13568 kVA - 77,6	Magnetically decoupled
Lp(A) a 0.3mt :	70 dB(A)	
Insulation Media	dry Type	Oil/dry
Transformer overall dimensions (LxWxH):	3600 x 1450 x 2640 mm	
Transformer weight	95000 kg	
Rated lightning impulse withstand voltage on primary side (not applicable in case of indoor installation)	Not applicable	125 kV peak
Rated lightning impulse withstand voltage on secondary side	Not applicable	Not applicable
Voltage class		IEC 60076-3
Accessories		
	Not applicable	Oil level alarms;
	PT100 sensor for temperature oil detection	
	Not applicable	Oil flow indicator (in the case of forced oil circulation);
	Not applicable	Air flow indicators (only for fan cooled transformers)

2.4 Preliminary Layout and connections design

2.4.1 Layout of CS2 and CS3 Transformers

In the drawing in fig. 3 is reported the "Layout of 27136 KVA, oil type transformers for CS2, CS3 Power supply".

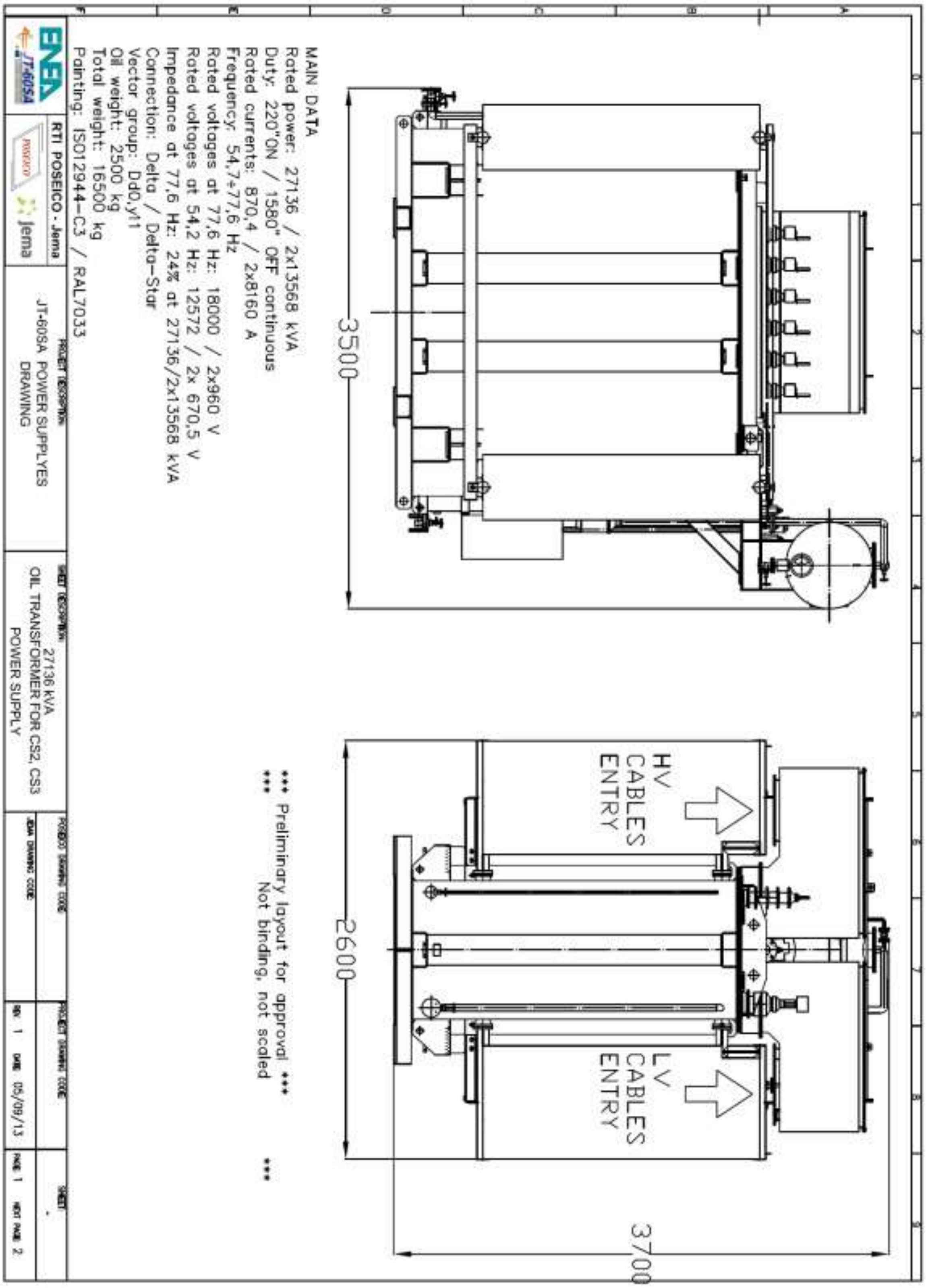


Fig. 3 – Preliminary layout of CS transformer.

2.4.2 Layout of FPPC transformers

In the drawing in fig.4 is reported the “Layout of 5220 kVA, dry type transformers for FPPC lower and FPPC upper Power Supply”.

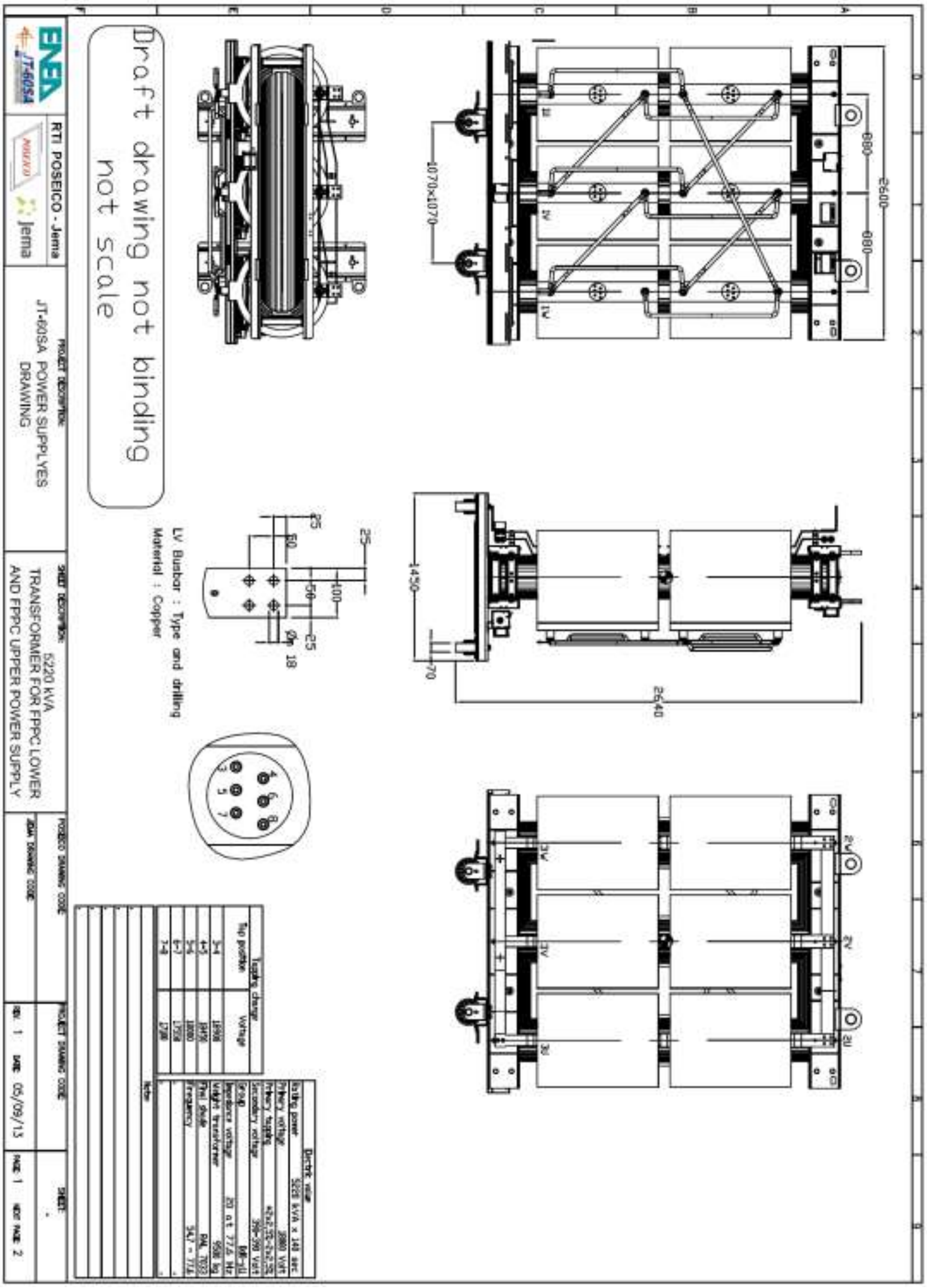


Fig. 4 – Preliminary layout of FPPC transformer.

3 Componentistica industriale dei sistemi di alimentazione

3.1 PS Design Criteria (General Features)

Main criteria for the design of power supplies are reported as follows:

- Thyristors Design criteria
- Modularity Criteria
- FMEA Analysis and Risk Mitigations Criteria
- Maintainability Criteria

In the next paragraphs each criterion is described in detail.

3.2 Thyristors Design Criteria

- Thyristors voltage capability based on Transformers Output Voltages for different PS and Voltage safety factor (defined as max repetitive peak forward blocking voltage/secondary transformer no-load RMS voltage) ≥ 3.5.
- Thyristors current and thermal design based on capability at nominal current waveform and at overcurrent due to short circuit after inductor for the different power supplies.
- All the thyristors of the different PS will be cooled, in bilateral way, using the same type of water cooling heat-sink.
- Minimum numbers of thyristors (maximum 2 in parallel) compatible with the above requirements in order to increase the bridges reliability.
- Thyristors power assemblies weight and layout dimension compatible with specified layout requirements
- It has been inserted a single fuse on DC output of each bridge leg of the different PSs. In the case of bidirectional bridge has been inserted a fuse only for both directions, as such directions operate alternatively (or one or the other) and a single fuse protects both.
- The characteristic of the fuses required for the different PSs were calculated in the document reported in next tables.

Table 5 – PS Design Summary

PS Design Summary Table: Input data from Technical Specifications and Design results														
													alternative solution	
Converter Type		Converter type			CS1	CS2	CS3	CS4	EF1	EF6	FPPC1	FPPC2	FPPC1	FPPC2
		Q.ty Bidirectional			2	2	2	2	1	1				
		Q.ty Unidirectional							1	1	4	4	4	4
		Configuration			Parallel	Parallel	Parallel	Parallel	Parallel	Parallel	Series/ antiparallel	Series/ antiparallel	Parallel/ antiparallel	Parallel/ antiparallel
Transformer	Nominal values	Power at Secondary winding		MVA	30,1	13,6	13,6	30,1	30,1	30,1	2,76	2,76	2,76	2,76
		Power of tranformer		MVA	2 x 30,1	2 x 13,6	2 x 13,6	2 x 30,1	2 x 30,1	2 x 30,1	2 x (2 x2,76)	2 x (2 x2,76)	2 x (2 x2,76)	2 x (2 x2,76)
		Secondary Voltage	V_{d0}	V	803,5	960	960	803,5	803,5	803,5	390	390	780	780
		Xcc			23,12%	24,00%	24,00%	23,12%	23,12%	23,12%	20,00%	20,00%	20,00%	20,00%
		K			0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
		F (Xcc)		Hz	77,60	77,60	77,60	77,60	77,60	77,60	77,60	77,60	77,60	77,60
	Extimated values	Potenza in corto	P_{cc}	kW	432	195	195	432	432	432	40	40	40	40
Operating Frequency		f_1		Hz	77,60	77,60	77,60	77,60	77,60	77,60	77,60	77,60	77,60	77,60
		f_2		Hz	54,20	54,20	54,20	54,20	54,20	54,20	54,20	54,20	54,20	54,20

Segue

PS Design Summary Table: Input data from Technical Specifications and Design results

													alternative solution	
		Converter type			CS1	CS2	CS3	CS4	EF1	EF6	FPPC1	FPPC2	FPPC1	FPPC2
Single Bridge	General Values	Nominal Current		A	10000	10000	10000	10000	10000	10000	5000	5000	2500	2500
		Max calculated DC current		A	26489	10017	10017	26489	26489	26489	5004	5004	2502	2502
		Nominal Voltage		V	1000	1300	1300	1000	1000	1000	2 x 500	2 x 500	1000	1000
		Calculated no load voltage	V_{d10}	V	1084,7	1296,0	1296,0	1084,7	1084,7	1084,7	526,5	526,5	1053,0	1053,0
		Calculated load voltage		V	1023,2	[illegible]	[illegible]	1023,2	1023,2	1023,2	[illegible]	[illegible]	[illegible]	[illegible]
		Converter Unbalance			5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
	Reactor	Resistance		Ω										
		Inductance		H	7,0E-04	7,0E-04	7,0E-04	7,0E-04	7,0E-04	7,0E-04	7,0E-04	7,0E-04	7,0E-04	7,0E-04
	Short Circuit before Smoothing Reactor	Permanent Current	I_{ccmax} @ f_1	kA	7,0E-04	7,0E-04	7,0E-04	4,2E+04	7,0E-04	132,5	28,9	28,9	14,4	14,4
		Permanent Current	I_{ccmax} @ f_2	kA	189,4	69,0	69,0	189,4	189,4	189,4	41,4	41,4	20,7	20,7
		Peak Current	I_{ccpeak} @ f_1	kA	215,6	78,6	78,6	215,6	215,6	215,6	47,1	47,1	23,5	23,5
		Peak Current	I_{ccpeak} @ f_2	kA	308,7	112,5	112,5	308,7	308,7	308,7	67,4	67,4	33,7	33,7
	Short Circuit after Smoothing Reactor	Max Peak Current	$I_{L,ccpeak}$ @ f_1	kA	16,7	18,0	18,0	16,7	16,7	16,7	8,2	8,2	9,0	9,0
		Max Peak Current	$I_{L,ccpeak}$ @ f_2	kA	19,5	21,4	21,4	19,5	19,5	19,5	9,6	9,6	11,8	11,8
		Equivalent RMS Current	$I_{L,ccrms}$ @ f_1	kA	9,1	9,8	9,8	9,1	9,1	9,1	4,5	4,5	5,1	5,1
		Equivalent RMS Current	$I_{L,ccrms}$ @ f_2	kA	10,7	11,8	11,8	10,7	10,7	10,7	5,3	5,3	6,8	6,8
Water Cooling System	General Values	Max ΔT, allowed		°C	10	10	10	10	10	10	10	10	10	10
		Max inlet Temperature		°C	35	35	35	35	35	35	35	35	35	35
		Max allowed flow rate		m^3/h	24	24	24	24	24	24	24	24	24	24
		Steady State Total DT_{H2O}	Double Side	°C	8,7	9,2	9,2	8,7	8,7	8,7	6,5	6,5	3,3	3,3
		Calculated flow rate	Double Side	m^3/h	18,00	21,00	21,00	18,00	14,40	14,40	10,80	10,80	10,80	10,80
Heatsink	General Values	Heatsink type			L160W160	L160W160	L160W160	L160W160	L160W160	L160W160	L160W160	L160W160	L160W160	L160W160
		Nominal flow Rate	Q	l/min	5	6	6	5	5	5	5	5	5	5
		R_{th} Double side	@ Q	°C/kW	4	3,6	3,6	4	4	4	4	4	4	4

Segue

PS Design Summary Table: Input data from Technical Specifications and Design results														
													alternative solution	
		Converter type			CS1	CS2	CS3	CS4	EF1	EF6	FPPC1	FPPC2	FPPC1	FPPC2
Device		Teoretical voltage		V	2820	3360	3360	2820	2820	2820	1370	1370	2730	2730
	General Values	V_{DRM}/V_{RRM}		V	2900	3400	3400	2900	2900	2900	1400	1400	2800	2800
		Component type			AT940P29	AT970P34	AT970P34	AT940P29	AT940P29	AT940P29			AT847S28	AT847S28
		Surge	I_{tsm}	kA	75	60	60	75	75	75	60	60	39,2	39,2
		Forward drop	V_{T0}	V	1	1,12	1,12	1	1	1	0,92	0,92	0,85	0,85
		On-State Resistance	r_T	mΩ	0,070	0,112	0,112	0,070	0,070	0,070	0,080	0,080	0,175	0,175
		R_{th} Double side		°C/kW	7,5	7,5	7,5	7,5	7,5	7,5	11	11	11	11
		Max Junction Temperature		°C	125	125	125	125	125	125	125	125	125	125
		Coefficient 1	A_1	°C/kW	2,67E+00	2,67E+00	2,67E+00	2,67E+00	2,67E+00	2,67E+00	6,32E+00	6,32E+00	6,32E+00	6,32E+00
		Time Constant 1	τ_1	s	2,50E+00	2,50E+00	2,50E+00	2,50E+00	2,50E+00	2,50E+00	1,80E+00	1,80E+00	1,80E+00	1,80E+00
		Coefficient 2	A_2	°C/kW	1,49E+00	1,49E+00	1,49E+00	1,49E+00	1,49E+00	1,49E+00	1,82E+00	1,82E+00	1,82E+00	1,82E+00
		Time Constant 2	τ_2	s	1,95E+00	1,95E+00	1,95E+00	1,95E+00	1,95E+00	1,95E+00	1,60E-01	1,60E-01	1,60E-01	1,60E-01
		Coefficient 3	A_3	°C/kW	1,49E+00	1,49E+00	1,49E+00	1,49E+00	1,49E+00	1,49E+00	4,84E-01	4,84E-01	4,84E-01	4,84E-01
		Time Constant 3	τ_3	s	2,50E-01	2,50E-01	2,50E-01	2,50E-01	2,50E-01	2,50E-01	3,00E-02	3,00E-02	3,00E-02	3,00E-02
		Coefficient 4	A_4	°C/kW	3,55E-01	3,55E-01	3,55E-01	3,55E-01	3,55E-01	3,55E-01	3,78E-01	3,78E-01	3,78E-01	3,78E-01
		Time Constant 4	τ_4	s	1,00E-05	1,00E-05	1,00E-05	1,00E-05	1,00E-05	1,00E-05	1,00E-03	1,00E-03	1,00E-03	1,00E-03
		Contact Thermal Resistance		°C/kW	1,50E+00	1,50E+00	1,50E+00	1,50E+00	1,50E+00	1,50E+00	2,00E+00	2,00E+00	2,00E+00	2,00E+00
		120° Conduction Add term		°C/kW	7,10E-01	7,10E-01	7,10E-01	7,10E-01	7,10E-01	7,10E-01	1,09E+00	1,09E+00	1,09E+00	1,09E+00
		Device Unbalance		%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
	Design Values	N° of electrically parallel device	N_c		2	2	2	2	2	2	1	1	1	1
		N° of in series cooling devices Double Side	N_{CDS}		1	1	1	1	1	1	1	1	1	1
	Withstand First Short Circuit Peak before Smoothing reactor	Minimum Peak Current		kA	86,3	31,4	31,4	86,3	86,3	86,3	47,1	47,1	23,5	23,5
		Short Circuit Pulse Duration		ms	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6	17,6
		Calculated N° of parallel	$N_{p,s,s}$		6	3	3	6	6	6	2	2	2	2
		N° of electrically parallel device	N_c		2	2	2	2	2	2	1	1	1	1
	Withstand Short Circuit after Smoothing Reactor (rectangular waveform, Peak Value, worst case)	Calculated N° of parallel			2	2	2	2	2	2	1	1	2	2
		N° of electrically parallel device	N_c		2	2	2	2	2	2	1	1	1	1
		ΔT_j for Short Circuit		°C	30,6	28,3	28,3	30,6	30,6	30,6	27,1	27,1	31,3	31,3
		Max T_j Double side	@ $I_{s,c,max}$		102,6	108,5	108,5	102,6	102,6	102,6	98,7	98,7	84,7	84,7
	Withstand Steady State Nominal Current	Steady State T_j	Double Side	°C	71,9	80,3	80,3	71,9	71,9	71,9	71,6	71,6	53,4	53,4

Table 6 - Characteristics of power assembly.

Power assembly type	Converter Type	Thyristor type	Thyristor voltage	Thyristor diameter	Dimension (W x L x H) (mm)	Mounted in PS
Type A	Bidirectional (4 thyristors)	AT940P29	2900 V	100 mm	480 x 240 x 574	CS1 – CS4 – EF1 –EF6
Type B	Bidirectional (4 thyristors)	AT970P34	3400 V	100 mm	480 x 240 x 574	CS2 – CS3
Type C	Unidirectional (2 thyristors)	AT940P29	2900 V	100 mm	480 x 240 x 447	EF1 - EF6
Type D	Unidirectional (2 thyristors)	AT738P14	1400 V	75 mm	480 x 240 x 447	Series configuration for FPPC1 – FPPC2
Type E	Unidirectional (2 thyristors)	AT738P14	1400 V	75 mm	480 x 240 x 447	Series configuration for FPPC1 – FPPC2
Type F	Unidirectional (2 thyristors)	AT847S28	2800 V	75 mm	480 x 240 x 447	Parallel configuration for FPPC1 – FPPC2
Type G	Unidirectional (2 thyristors)	AT847S28	2800 V	75 mm	480 x 240 x 447	Parallel configuration for FPPC1 – FPPC2

3.3 Modularity of Thyristor Power Assemblies

In order to obtain the maximum modularity in the different Power Supplies all the configurations have been realized using only 5 type of different power assemblies (power stack), that use only 3 type of thyristors with 2 different diameters. All the gate board are equal.

3.4 FMEA Analysis and Risk Mitigations for Power supplies

A complete FMEA Failure Modes and Effects Analysis, including Risk Mitigation has been developed in order to respect the specified data reported in the following specified Criticality Matrix

Table 7 – FMEA analysis including risk mitigation.

Breakdown (including fault analysis time)	**Very frequent** Max 12/year	**Frequent** Max 2/year	**Rare** Max 1/year	**Improbable** Max 0.2/year	**"Acceptable" breakdown duration**
Catastrophic shutdown > 24 h	Unacceptable	Unacceptable	Unacceptable	Unacceptable	**0 h/year**
Critical 8 h < shutdown < 24 h average = 16 h	Unacceptable	Unacceptable	Unacceptable	Acceptable	**0.2×16 = 3.2 h/year**
Major 2 h < shutdown < 8 h average = 5 h	Unacceptable	Unacceptable	Acceptable	Acceptable	**1×5+0.2×5 = 6 h/year**
Minor shutdown < 2 h average = 1 h	Unacceptable	Acceptable	Acceptable	Acceptable	**2×1+1×1+0.2×1 = 3.2 h/year**

The FMEA Analysis and Risk mitigation for the different PS is reported in tables.

Table 8 – Matrix of criticalities

		Frequency				"Acceptable" breakdown duration
		Very Frequent	Frequent	Rare	Improbable	
Severity	Catastrophic	Unacceptable	Unacceptable	Unacceptable	Unacceptable	0 h/year
	Critical	Unacceptable	Unacceptable	Unacceptable	Acceptable	0.2x16 = 3.2 h/year
	Major	Unacceptable	Unacceptable	Acceptable	Not Critical	1x5+0.2x5 = 6 h/year
	Minor	Unacceptable	Acceptable	Not Critical	Not Critical	2x1+1x1+0.2x1= 3.2h/year

CHECK		
Sev.	Catastrophic	Unacceptable
Freq.	Very Frequent	

Breakdown (including Fault Analysis Time)	
Catastrophic	shutdown > 24 h
Critical	8 h < shutdown < 24 h average = 16 h
Major	2 h < shutdown < 8 h average = 5 h
Minor	shutdown < 2h

FREQUENCY (Max ev/year)	
Very Frequent	12
Frequent	2
Rare	1
Improbable	0,2

Table 9 – CS1, CS4 Matrix of criticalities

Machinery: CS1, CS4										
Failure Mode		Failure Effects	Mitigation Measures	Initial Criticality			Final Criticality			Remarks
				Failure Severity	Failure Frequency	Failure Criticality	Failure Severity	Failure Frequency	Failure Criticality	
Short circuit before interbridge reactor	Short circuit between positive and negative bar	Potential failure of semiconductor devices on two or three branches of the bridge	Use of semiconductor protection fuses to avoid thyristors damage (only fuses must be replaced)	Catastrophic	Improbable	Unacceptable	Major	Improbable	Not Critical	Calculated short circuit current 308.7kA For bridge
Short circuit after interbridge reactor	Short circuit between positive and negative bar	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	- Calculated short circuit current: 39kA - Effects estimated in case of blocking of the Control System
Internal short circuit due to failure of a semiconductor device	Short circuit due to failure of a SCR in reverse bias	- Potential explosion of a device - Overvoltage on inductor	Use of semiconductor protection fuses to avoid the explosion of failed thyristors (The failed thyristor and fuses must be replaced)	Critical	Improbable (0.08 [ev/year])	Acceptable	Major	Improbable	Not Critical	- Calculated short circuit current: 308.7kA For bridge
Control System failure	SCRs not triggered	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	Calculated short circuit current: 39kA

Table 10 – CS2, CS3 Matrix of criticalities

Machinery: CS2, CS3										
Failure Mode		Failure Effects	Mitigation Measures	Initial Criticality			Final Criticality			Remarks
				Failure Severity	Failure Frequency	Failure Criticality	Failure Severity	Failure Frequency	Failure Criticality	
Short circuit before interbridge reactor	Short circuit between positive and negative bar	Potential failure of semiconductor devices on two or three branches of the bridge	Use of semiconductor protection fuses to avoid thyristors damage (only fuses must be replaced)	Catastrophic	Improbable	Unacceptable	Major	Improbable	Not Critical	Calculated short circuit current:112,5kA For bridge
Short circuit after interbridge reactor	Short circuit between positive and negative bar	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	- Calculated short circuit current: 42,8kA - Effects estimated in case of blocking of the Control System
Internal short circuit due to failure of a semiconductor device	Short circuit due to failure of a SCR in reverse bias	- Potential explosion of a device - Overvoltage on inductor	Use of semiconductor protection fuses to avoid the explosion of failed thyristors (The failed thyristor and fuses must be replaced)	Critical	Improbable (0.08 [ev/year])	Acceptable	Major	Improbable	Not Critical	- Calculated short circuit current: 112.5kA For Bridge
Control System failure	SCRs not triggered	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	Calculated short circuit current: 42.8kA

Table 11 – EF1, EF6 Matrix of criticalities

Machinery: EF1, EF6										
Failure Mode		Failure Effects	Mitigation Measures	Initial Criticality			Final Criticality			Remarks
				Failure Severity	Failure Frequency	Failure Criticality	Failure Severity	Failure Frequency	Failure Criticality	
Short circuit before interbridge reactor	Short circuit between positive and negative bar	Potential failure of semiconductor devices on two or three branches of the bridge	Use of semiconductor protection fuses to avoid thyristors damage (only fuses must be replaced)	Catastrophic	Improbable	Unacceptable	Major	Improbable	Not Critical	Calculated short circuit current:308.7kA For bridge
Short circuit after interbridge reactor	Short circuit between positive and negative bar	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	- Calculated short circuit current: 39kA - Effects estimated in case of blocking of the Control System
Internal short circuit due to failure of a semiconductor device	Short circuit due to failure of a SCR in reverse bias	- Potential explosion of a device - Overvoltage on inductor	Use of semiconductor protection fuses to avoid the explosion of failed thyristors (The failed thyristor and fuses must be replaced)	Critical	Improbable (0.04 [ev/year])	Acceptable	Major	Improbable	Not Critical	- Calculated short circuit current: 308.7kA For bridge
Control System failure	SCRs not triggered	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	Calculated short circuit current: 39kA

Table 12 – FPPC1, FPPC2 Matrix of criticalities

Machinery: FPPC1, FPPC2										
Failure Mode		Failure Effects	Mitigation Measures	Initial Criticality			Final Criticality			Remarks
				Failure Severity	Failure Frequency	Failure Criticality	Failure Severity	Failure Frequency	Failure Criticality	
Short circuit before interbridge reactor	Short circuit between positive and negative bar	Potential failure of semiconductor devices on two or three branches of the bridge	Use of semiconductor protection fuses to avoid thyristors damage (only fuses must be replaced)	Catastrophic	Improbable	Unacceptable	Major	Improbable	Not Critical	Calculated short circuit current:67,4kA For bridge
Short circuit after interbridge reactor	Short circuit between positive and negative bar	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	- Calculated short circuit current: 19,2kA - Effects estimated in case of blocking of the Control System
Internal short circuit due to failure of a semiconductor device	Short circuit due to failure of a SCR in reverse bias	- Potential explosion of a device - Overvoltage on inductor	Use of semiconductor protection fuses to avoid the explosion of failed thyristors (The failed thyristor and fuses must be replaced)	Critical	Improbable (0.04 [ev/year])	Acceptable	Major	Improbable	Not Critical	- Calculated short circuit current: 67,4kA For bridge
Control System failure	SCRs not triggered	No Effects	None	Minor	Frequent	Acceptable	Minor	Frequent	Acceptable	Calculated short circuit current: 19,2kA

3.5 Maintainability Criteria for Thyristors Cubicle

In order to obtain a very easy maintainability of PSs we have realized the following actions:

- The power assembly (power stack) is sub-assembled unit that must be replaced in case of fail.
- The fuse and the relative micro-switch signal can been used to easy select of failed stack.
- The number of different sub-assemblies and components (devices, stack, etc.) has been used to reduce the spare parts of power stacks.
- Quick-release couplings on the hydraulic.
- Easy disassembly.

3.6 SCR Rectifier Technical Specifications

3.6.1 Thyristors Data Sheets

All PSs have been realized using only 4 types of the different thyristors in order to obtains the maximum of modularity and to reduce cost of spare parts and maintenance management. In the following table the type of thyristor used in the different Power Supplies is reported.

Table 13 – Type of thyristor for each PS (All the devices are designed and manufactured by POSEICO).

Power Supply	Thyristor code	VDRM, VRRM (V)	ITSM (KA)	Total Quantity (for 1 PS)	Data sheet Code /Issue
CS1	AT940P29	2900 V	75	48	AT940 issue 04
CS2	AT970P34	3400 V	60	48	AT970 issue 00
CS3	AT970P34	3400 V	60	48	AT970 issue 00
CS4	AT940P29	2900 V	75	48	AT940 issue 04
EF1	AT940P29	2900 V	75	36	AT940 issue 04
EF2	AT940S26	2600 V	75	36	AT940 issue 04
FPPC1 upper Series Conf.	AT738S14	1400 V	60	24	AT738 issue 04
FPPC2 lower Series Conf.	AT738S14	1400 V	60	24	AT970 issue 04
FPPC1 upper Parallel Conf.	AT847S28	2800 V	39.2	24	AT847 issue 05
FPPC2 lower Parallel Conf.	AT847S28	2800 V	39.2	24	AT847 issue 05

3.6.2 Data sheet AT940P29 / AT940S26

In the next pages are reported the Data sheet AT940 issue 04

POSEICO

POSEICO SPA
POwer SEmiconductors Italian COrporation

POSEICO SPA
Via Pillea 42-44, 16153 Genova - ITALY
Tel. + 39 010 8599400 - Fax + 39 010 8682006
Sales Office:
Tel. + 39 010 8599400 - Fax + 39 010 8681180

PHASE CONTROL THYRISTOR

AT940

Repetitive voltage up to	**2900 V**
Mean on-state current	**4687 A**
Surge current	**75 kA**

FINAL SPECIFICATION

Aug. 13 - Issue: 4

Symbol	Characteristic	Conditions	Tj [°C]	Value	Unit
BLOCKING					
V_{RRM}	Repetitive peak reverse voltage		125	2900	V
V_{RSM}	Non-repetitive peak reverse voltage		125	3000	V
V_{DRM}	Repetitive peak off-state voltage		125	2900	V
I_{RRM}	Repetitive peak reverse current	V=VRRM	125	300	mA
I_{DRM}	Repetitive peak off-state current	V=VDRM	125	300	mA
CONDUCTING					
$I_{T(AV)}$	Mean on-state current	180° sin, 50 Hz, Th=55°C, double side cooled		4687	A
$I_{T(AV)}$	Mean on-state current	180° sin, 50 Hz, Tc=85°C, double side cooled		3638	A
I_{TSM}	Surge on-state current	sine wave, 10 ms	125	75,0	kA
I^2t	I^2t	without reverse voltage		28125 x1E3	A^2s
V_T	On-state voltage	On-state current = 7500 A	25	1,56	V
$V_{T(TO)}$	Threshold voltage		125	1,00	V
r_T	On-state slope resistance		125	0,070	mohm
SWITCHING					
di/dt	Critical rate of rise of on-state current, min.	From 75% VDRM, gate 10V 5ohm	125	200	A/µs
dv/dt	Critical rate of rise of off-state voltage, min.	Linear ramp up to 70% of VDRM	125	1000	V/µs
td	Gate controlled delay time, typical	VD=100V, gate source 10V, 10 ohm , tr=5 µs	25		µs
tq	Circuit commutated turn-off time, typical	dv/dt = 20 V/µs linear up to 75% VDRM		500	µs
Q_{RR}	Reverse recovery charge	di/dt=-20 A/µs, I= 2150 A	125		µC
I_{RR}	Peak reverse recovery current	VR= 50 V			A
I_H	Holding current, typical	VD=5V, gate open circuit	25	500	mA
I_L	Latching current, typical	VD=12V, tp=30µs	25	1000	mA
GATE					
V_{GT}	Gate trigger voltage	VD=12V	25	3,5	V
I_{GT}	Gate trigger current	VD=12V	25	400	mA
V_{GD}	Non-trigger gate voltage, min.	VD=VDRM	125	0,25	V
V_{FGM}	Peak gate voltage (forward)			10	V
I_{FGM}	Peak gate current			10	A
V_{RGM}	Peak gate voltage (reverse)			10	V
P_{GM}	Peak gate power dissipation	Pulse width 100 µs		150	W
P_G	Average gate power dissipation			3	W
MOUNTING					
$R_{th(j-c)}$	Thermal impedance, DC	Junction to case, double side cooled		6,0	°C/kW
$R_{th(c-h)}$	Thermal impedance	Case to heatsink, double side cooled		1,5	°C/kW
T_j	Operating junction temperature			-30 / 125	°C
F	Mounting force			80/ 100	kN
	Mass			3000	g

ORDERING INFORMATION : AT940 S 29

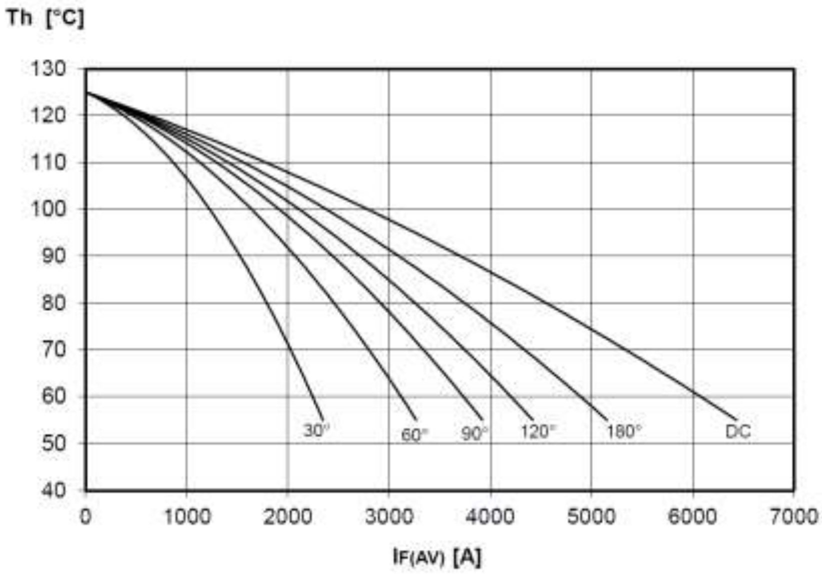
standard specification (S) — VDRM&VRRM/100 (29)

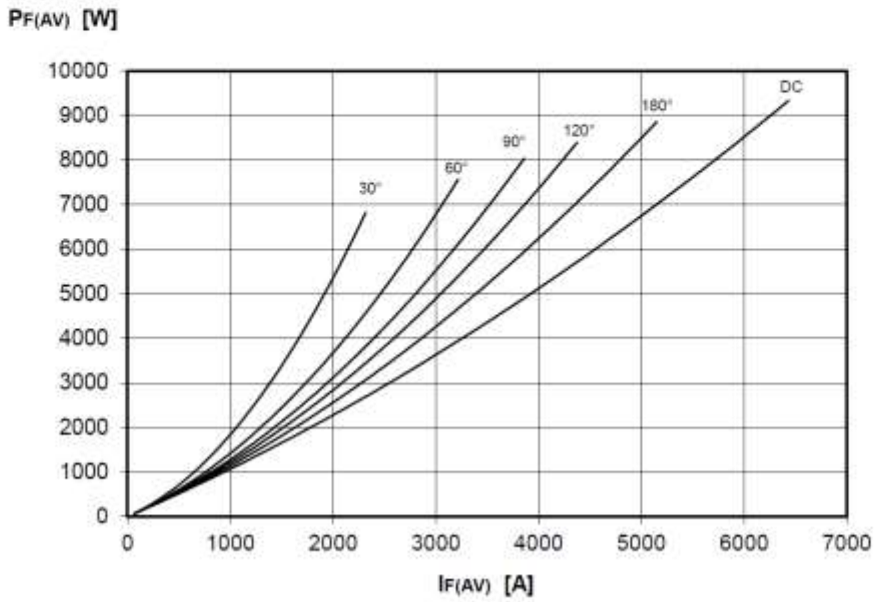
AT940 PHASE CONTROL THYRISTOR

FINAL SPECIFICATION Aug. 13 - Issue: 4

DISSIPATION CHARACTERISTICS

SQUARE WAVE





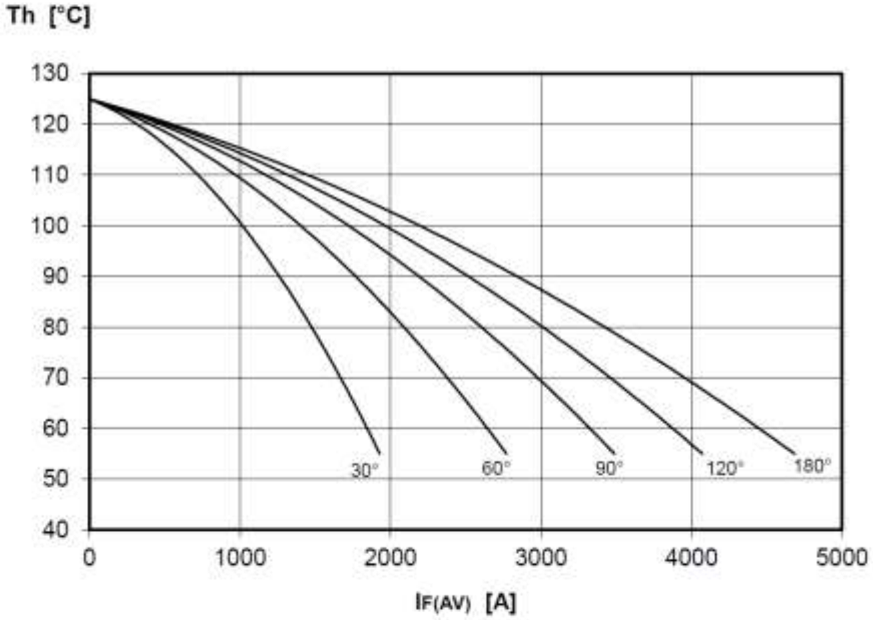
AT940 PHASE CONTROL THYRISTOR

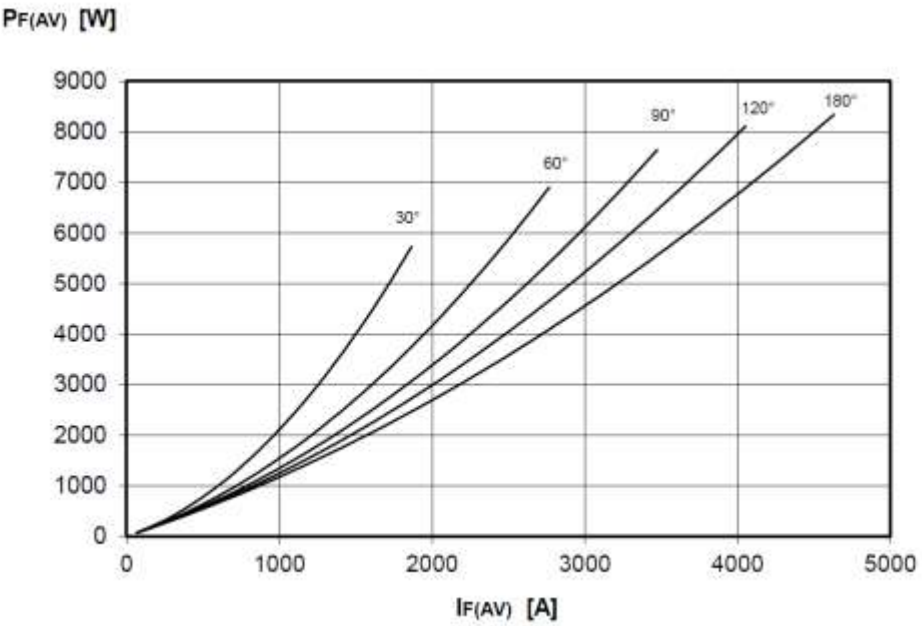
POSEICO

FINAL SPECIFICATION Aug. 13 - Issue: 4

DISSIPATION CHARACTERISTICS

SINE WAVE

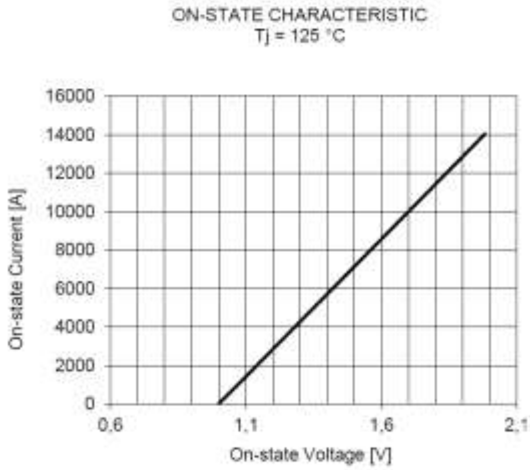


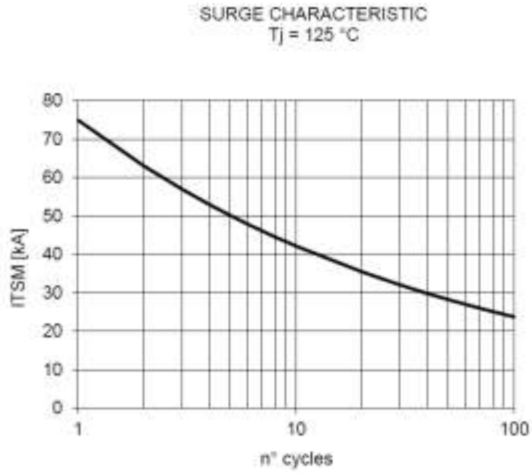


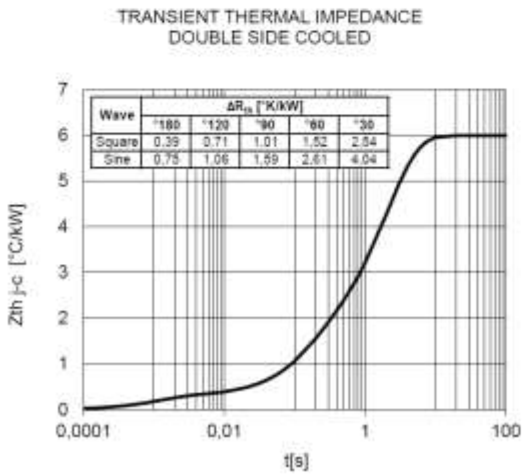
AT940 PHASE CONTROL THYRISTOR

POSEICO

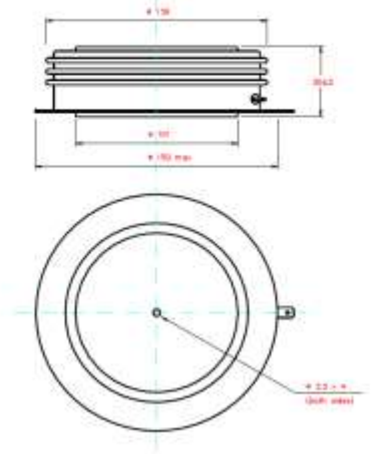
FINAL SPECIFICATION Aug. 13 - Issue: 4







Wave	ΔR_{th} [°K/kW]				
	°180	°120	°90	°60	°30
Square	0.39	0.71	1.01	1.52	2.84
Sine	0.75	1.06	1.59	2.61	4.04



$$Z_{th\ j-c}(t) = \sum_{i=1}^{n} A_i * \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

i	1	2	3	4
A_i [°C/kW]	2,738	1,779	1,186	0,297
τ_i [s]	2,4	1,70	0,16	0,001

Cathode terminal type DIN 46244 - A 4.8 - 0.8

Gate terminal type AMP 60598 - 1

All the characteristics given in this data sheet are guaranteed only with uniform clamping force, cleaned and lubricated heatsink, surfaces with flatness < .03 mm and roughness < 2 µm.
In the interest of product improvement POSEICO SpA reserves the right to change any data given in this data sheet at any time without previous notice.
If not stated otherwise the maximum value of ratings (simbols over shaded background) and characteristics is reported.

Distributed by

3.6.3 Data Sheet AT970P34

In the next pages are reported the Data sheet AT970 issue 00

POSEICO

POSEICO SPA
POwer SEmiconductors Italian COrporation

POSEICO SPA
Via Pillea 42-44, 16153 Genova - ITALY
Tel. + 39 010 8599400 - Fax + 39 010 8682006
Sales Office:
Tel. + 39 010 8599400 - Fax + 39 010 8681180

PHASE CONTROL THYRISTOR

AT970

Repetitive voltage up to **3400 V**

Mean on-state current **3872 A**

Surge current **68 kA**

TARGET SPECIFICATION

Sept. 13 - Issue: 0

Symbol	Characteristic	Conditions	Tj [°C]	Value	Unit
BLOCKING					
V_{RRM}	Repetitive peak reverse voltage		125	3400	V
V_{RSM}	Non-repetitive peak reverse voltage		125	3500	V
V_{DRM}	Repetitive peak off-state voltage		125	3400	V
I_{RRM}	Repetitive peak reverse current	V=VRRM	125	300	mA
I_{DRM}	Repetitive peak off-state current	V=VDRM	125	300	mA
CONDUCTING					
$I_{T(AV)}$	Mean on-state current	180° sin, 50 Hz, Th=55°C, double side cooled		3872	A
$I_{T(AV)}$	Mean on-state current	180° sin, 50 Hz, Tc=85°C, double side cooled		3027	A
I_{TSM}	Surge on-state current	sine wave, 10 ms	125	68,0	kA
I^2t	I^2t	without reverse voltage		23120 x1E3	A²s
V_T	On-state voltage	On-state current = 7500 A	25	1,95	V
$V_{T(TO)}$	Threshold voltage		125	1,12	V
r_T	On-state slope resistance		125	0,112	mohm
SWITCHING					
di/dt	Critical rate of rise of on-state current, min.	From 67% VDRM, gate 10V 5ohm	125	200	A/µs
dv/dt	Critical rate of rise of off-state voltage, min.	Linear ramp up to 67% of VDRM	125	1000	V/µs
td	Gate controlled delay time, typical	VD=100V, gate source 10V, 10 ohm , tr=5 µs	25		µs
tq	Circuit commutated turn-off time, typical	dv/dt = 20 V/µs linear up to 75% VDRM			µs
Q_{RR}	Reverse recovery charge	di/dt=-20 A/µs, I= 2150 A	125		µC
I_{RR}	Peak reverse recovery current	VR= 50 V			A
I_H	Holding current, typical	VD=5V, gate open circuit	25		mA
I_L	Latching current, typical	VD=12V, tp=30µs	25		mA
GATE					
V_{GT}	Gate trigger voltage	VD=12V	25	3,5	V
I_{GT}	Gate trigger current	VD=12V	25	250	mA
V_{GD}	Non-trigger gate voltage, min.	VD=67%VDRM	125	0,25	V
V_{FGM}	Peak gate voltage (forward)				V
I_{FGM}	Peak gate current				A
V_{RGM}	Peak gate voltage (reverse)				V
P_{GM}	Peak gate power dissipation	Pulse width 100 µs			W
P_G	Average gate power dissipation				W
MOUNTING					
$R_{th(j-c)}$	Thermal impedance, DC	Junction to case, double side cooled		6,0	°C/kW
$R_{th(c-h)}$	Thermal impedance	Case to heatsink, double side cooled		1,5	°C/kW
T_j	Operating junction temperature			-30 / 125	°C
F	Mounting force			80/ 100	kN
	Mass			3000	g

ORDERING INFORMATION : AT970 S 34

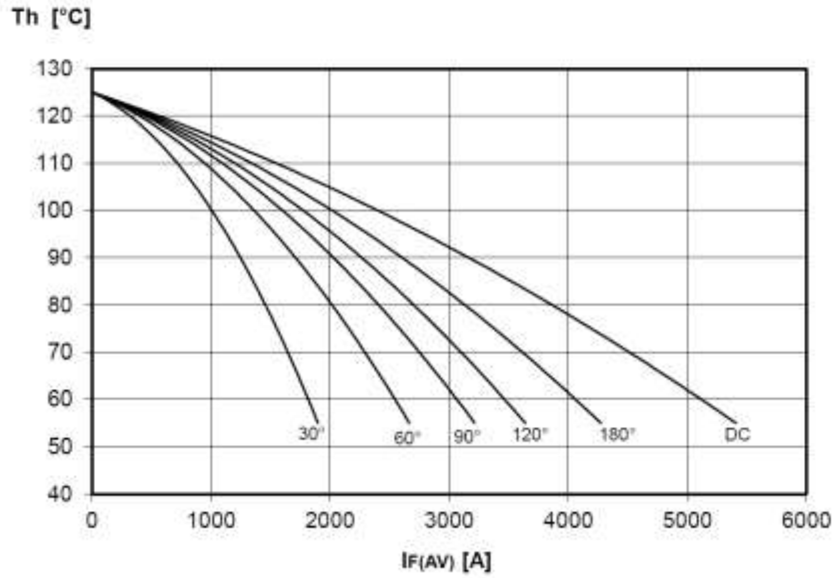
standard specification (S) — VDRM&VRRM/100 (34)

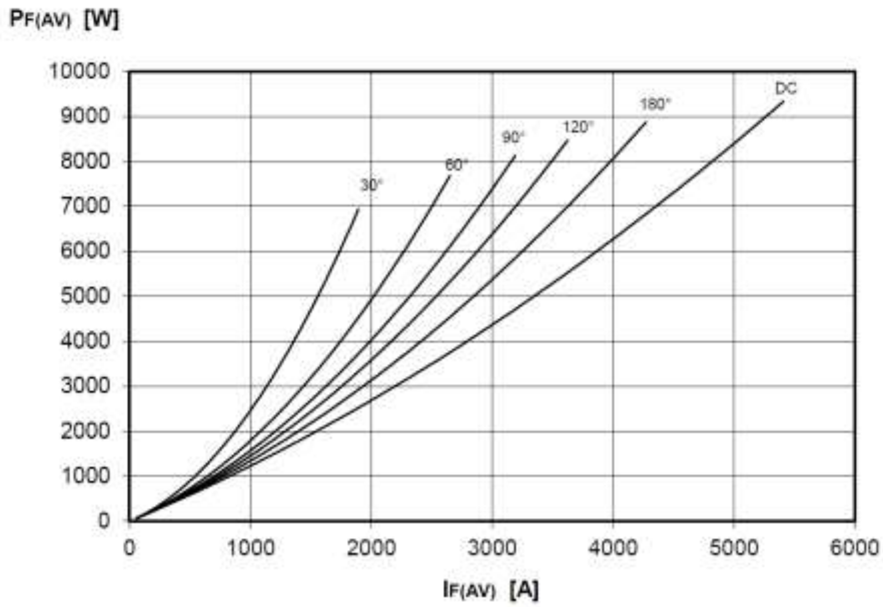
AT970 PHASE CONTROL THYRISTOR

TARGET SPECIFICATION Sept. 13 - Issue: 0

DISSIPATION CHARACTERISTICS

SQUARE WAVE





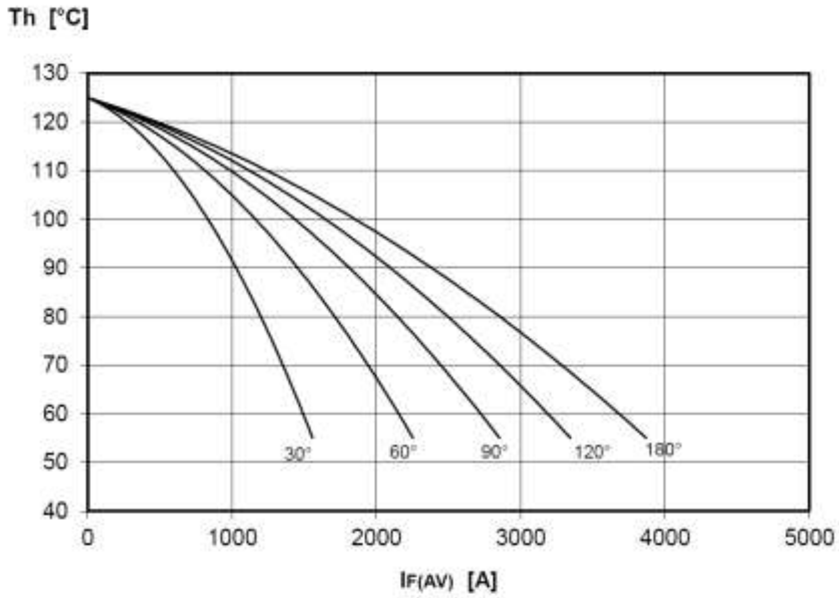
AT970 PHASE CONTROL THYRISTOR

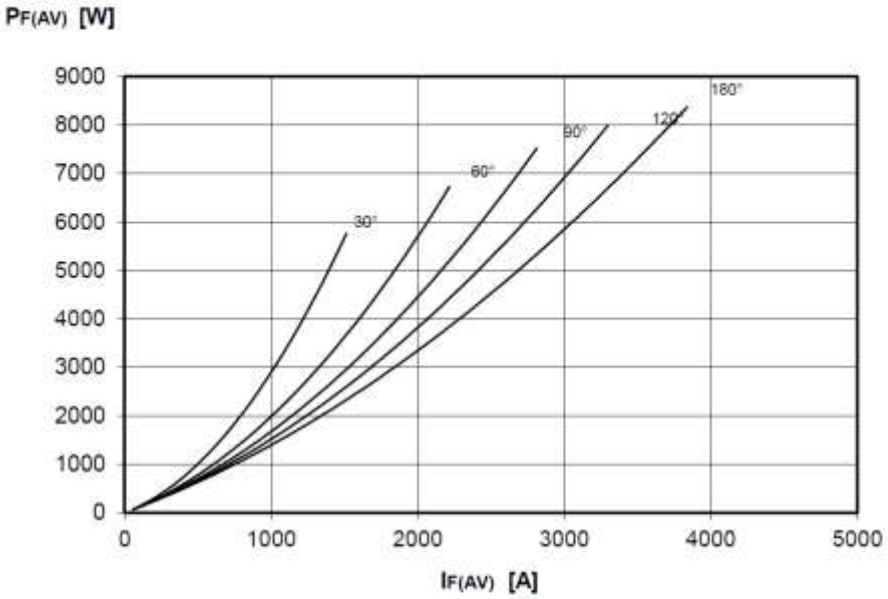
POSEICO

TARGET SPECIFICATION Sept. 13 - Issue: 0

DISSIPATION CHARACTERISTICS

SINE WAVE



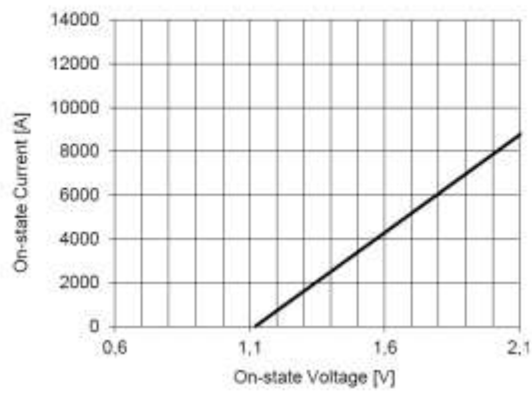


AT970 PHASE CONTROL THYRISTOR

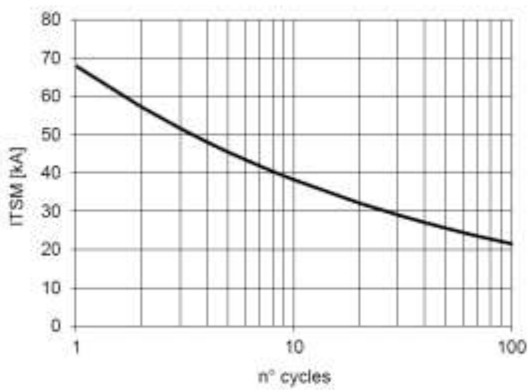
POSEICO

TARGET SPECIFICATION Sept. 13 - Issue: 0

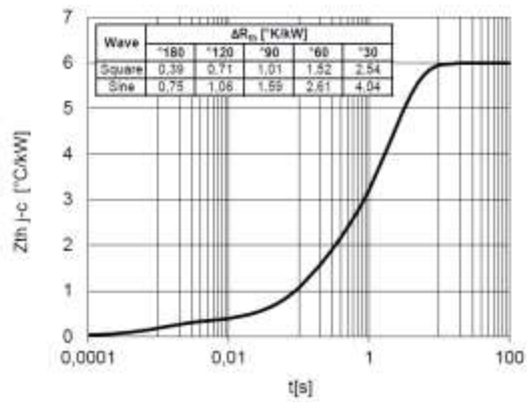
ON-STATE CHARACTERISTIC
Tj = 125 °C



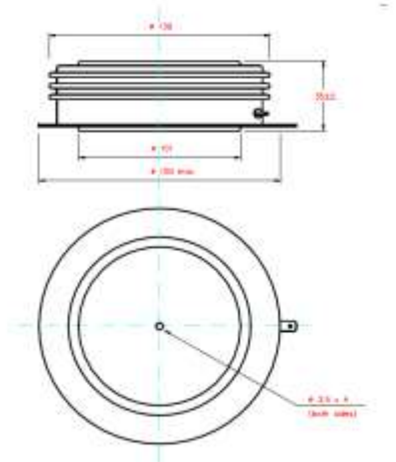
SURGE CHARACTERISTIC
Tj = 125 °C



TRANSIENT THERMAL IMPEDANCE
DOUBLE SIDE COOLED



Wave	ΔR_{th} [°K/kW]				
	°180	°120	°90	°60	°30
Square	0,39	0,71	1,01	1,52	2,54
Sine	0,75	1,06	1,55	2,61	4,04



$$Z_{th\ j-c}(t) = \sum_{i=1}^{n} A_i * \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

i	1	2	3	4
A_i [°C/kW]	2,738	1,779	1,186	0,297
τ_i [s]	2,4	1,70	0,16	0,001

Cathode terminal type DIN 46244 - A 4.8 - 0.8
Gate terminal type AMP 60598 - 1

All the characteristics given in this data sheet are guaranteed only with uniform clamping force, cleaned and lubricated heatsink, surfaces with flatness < .03 mm and roughness < 2 µm.
In the interest of product improvement POSEICO SpA reserves the right to change any data given in this data sheet at any time without previous notice.
If not stated otherwise the maximum value of ratings (simbols over shaded background) and characteristics is reported.

Distributed by

3.6.4 Data Sheet AT738P14

In the next pages are reported the Data sheet AT738 issue 04

POSEICO

POSEICO SPA
POwer SEmiconductors Italian COrporation

POSEICO SPA
Via Pillea 42-44, 16153 Genova - ITALY
Tel. + 39 010 8599400 - Fax + 39 010 8682006
Sales Office:
Tel. + 39 010 8599400 - Fax + 39 010 8681180

PHASE CONTROL THYRISTOR

AT738

Repetitive voltage up to	**2200 V**
Mean on-state current	**3426 A**
Surge current	**60 kA**

FINAL SPECIFICATION

Sept. 13 - Issue: 4

Symbol	Characteristic	Conditions	Tj [°C]	Value	Unit
BLOCKING					
V RRM	Repetitive peak reverse voltage		125	2200	V
V RSM	Non-repetitive peak reverse voltage		125	2300	V
V DRM	Repetitive peak off-state voltage		125	2200	V
I RRM	Repetitive peak reverse current	V=VRRM	125	200	mA
I DRM	Repetitive peak off-state current	V=VDRM	125	200	mA
CONDUCTING					
I T(AV)	Mean on-state current	180° sin, 50 Hz, Th=55°C, double side cooled		3426	A
I T(AV)	Mean on-state current	180° sin, 50 Hz, Tc=85°C, double side cooled		2622	A
I TSM	Surge on-state current	sine wave, 10 ms	125	60,0	kA
I² t	I² t	without reverse voltage		18000 x1E3	A²s
V T	On-state voltage	On-state current = 2000 A	25	1,10	V
V T(TO)	Threshold voltage		125	0,92	V
r T	On-state slope resistance		125	0,090	mohm
SWITCHING					
di/dt	Critical rate of rise of on-state current, min.	From 75% VDRM, gate 10V 5ohm	125	200	A/µs
dv/dt	Critical rate of rise of off-state voltage, min.	Linear ramp up to 75% of VDRM	125	500	V/µs
td	Gate controlled delay time, typical	VD=100V, gate source 25V, 10 ohm , tr=5 µs	25	3	µs
tq	Circuit commutated turn-off time, typical	dv/dt = 20 V/µs linear up to 80% VDRM		320	µs
Q RR	Reverse recovery charge	di/dt=-20 A/µs, I= 2000 A	125		µC
I RR	Peak reverse recovery current	VR= 50 V			A
I H	Holding current, typical	VD=5V, gate open circuit	25	300	mA
I L	Latching current, typical	VD=5V, tp=30µs	25	700	mA
GATE					
V GT	Gate trigger voltage	VD=5V	25	3,5	V
I GT	Gate trigger current	VD=5V	25	350	mA
V GD	Non-trigger gate voltage, min.	VD=VDRM	125	0,25	V
V FGM	Peak gate voltage (forward)			30	V
I FGM	Peak gate current			10	A
V RGM	Peak gate voltage (reverse)			5	V
P GM	Peak gate power dissipation	Pulse width 100 µs		150	W
P G	Average gate power dissipation			2	W
MOUNTING					
R th(j-c)	Thermal impedance, DC	Junction to case, double side cooled		9,0	°C/kW
R th(c-h)	Thermal impedance	Case to heatsink, double side cooled		2,0	°C/kW
T j	Operating junction temperature			-30 / 125	°C
F	Mounting force			40/ 50	kN
	Mass			1700	g

ORDERING INFORMATION : AT738 S 22

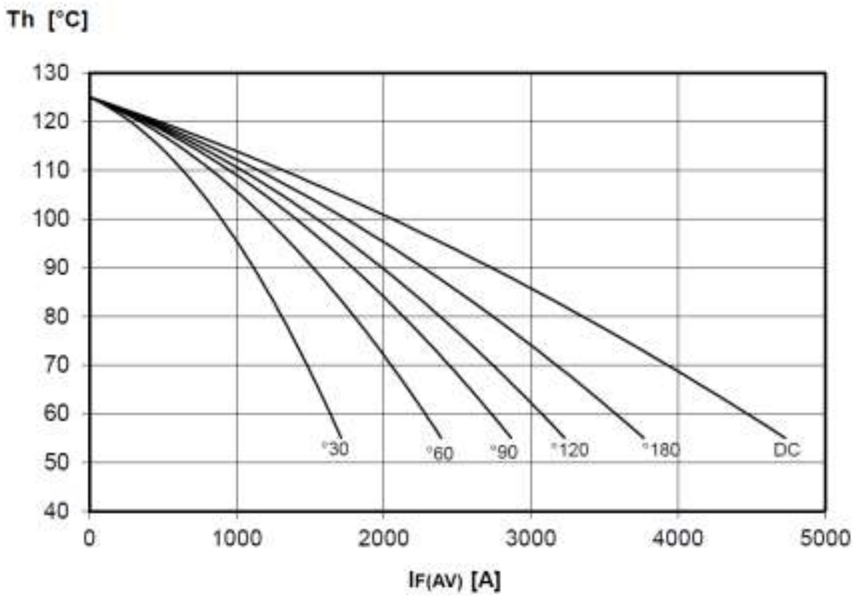
standard specification (S) — VDRM&VRRM/100 (22)

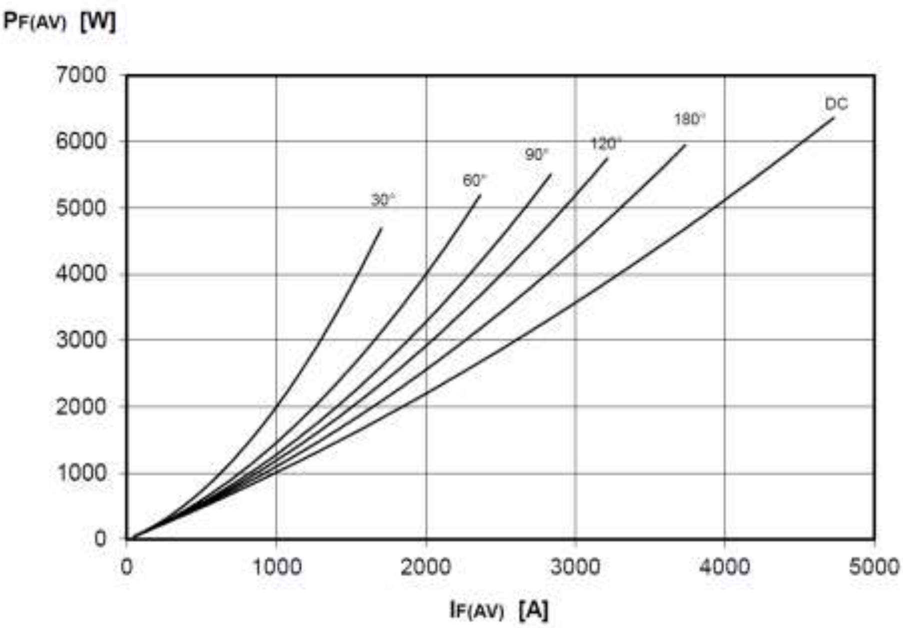
AT738 PHASE CONTROL THYRISTOR

FINAL SPECIFICATION Sept. 13 - Issue: 4

DISSIPATION CHARACTERISTICS

SQUARE WAVE





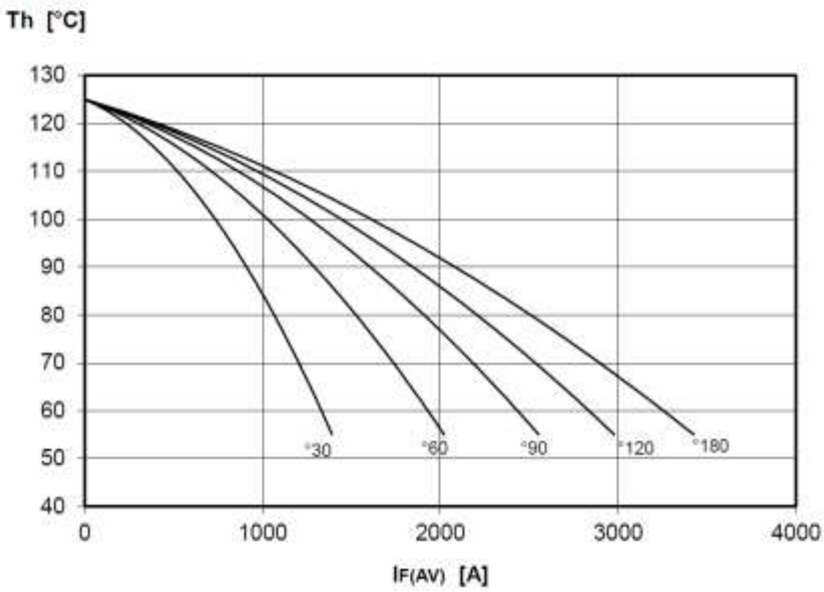
AT738 PHASE CONTROL THYRISTOR

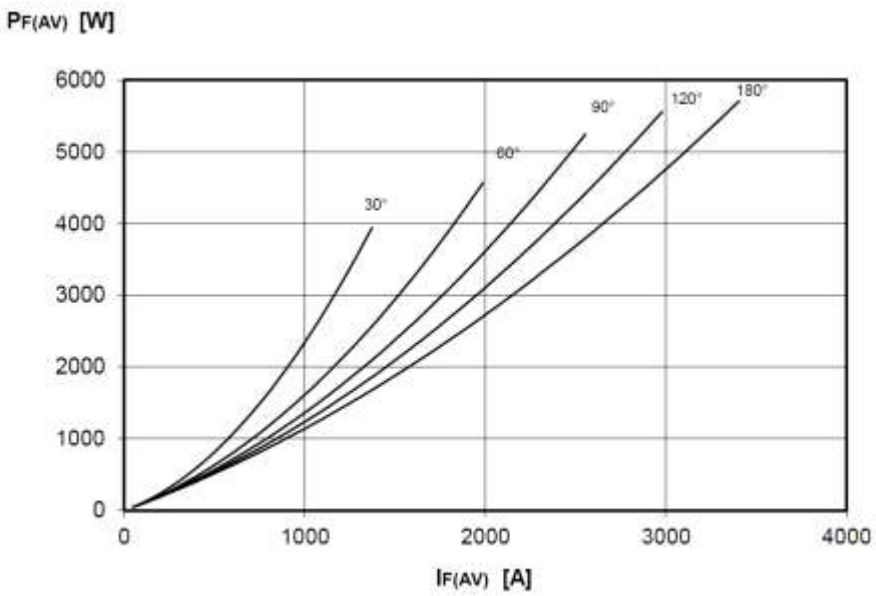
POSEICO

FINAL SPECIFICATION Sept. 13 - Issue: 4

DISSIPATION CHARACTERISTICS

SINE WAVE



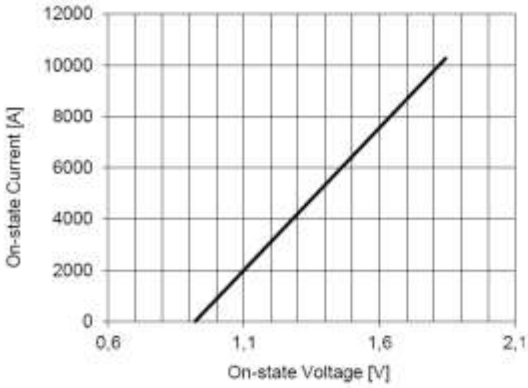


AT738 PHASE CONTROL THYRISTOR

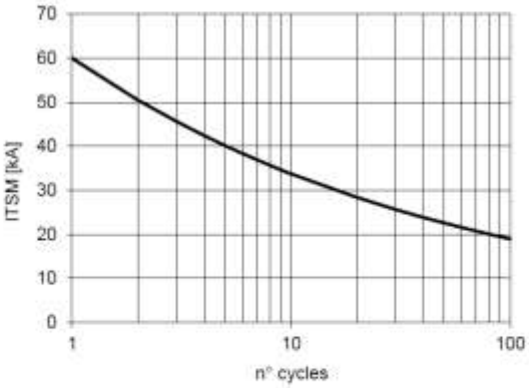
POSEICO

FINAL SPECIFICATION Sept. 13 - Issue: 4

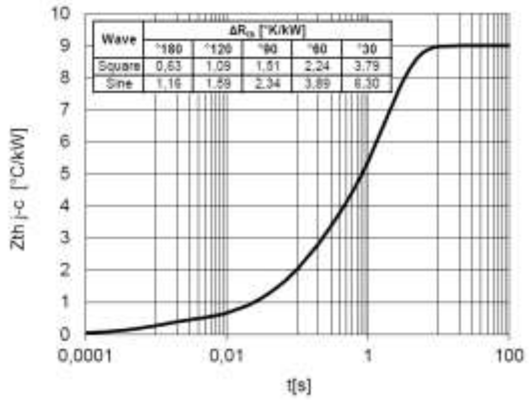
ON-STATE CHARACTERISTIC
Tj = 125 °C



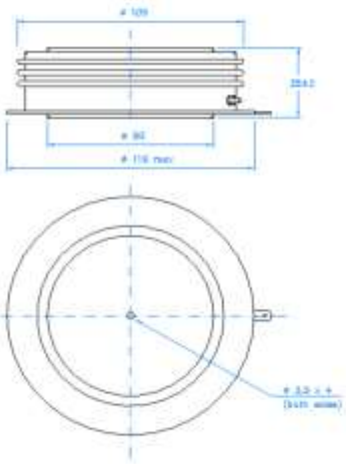
SURGE CHARACTERISTIC
Tj = 125 °C



TRANSIENT THERMAL IMPEDANCE
DOUBLE SIDE COOLED



Wave	ΔR$_{th}$ [°K/kW]				
	^180	^120	°90	°60	°30
Square	0,63	1,09	1,61	2,24	3,79
Sine	1,16	1,59	2,34	3,89	6,30



$$Z_{th\ j-c}(t) = \sum_{i=1}^{n} A_i * \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

i	1	2	3	4
A_i [°C/kW]	6,323	1,815	0,484	0,378
τ_i [s]	1,8	0,16	0,03	0,001

Cathode terminal type DIN 46244 - A 4.8 - 0.8
Gate terminal type AMP 60598 - 1

All the characteristics given in this data sheet are guaranteed only with uniform clamping force, cleaned and lubricated heatsink, surfaces with flatness < .03 mm and roughness < 2 µm.
In the interest of product improvement POSEICO SpA reserves the right to change any data given in this data sheet at any time without previous notice.
If not stated otherwise the maximum value of ratings (simbols over shaded background) and characteristics is reported.

Distributed by

ENEA
RICERCA DI SISTEMA ELETTRICO

3.6.5 Data Sheet AT847S28

In the next pages are reported the Data sheet AT847 issue 05

POSEICO
POSEICO SPA
POwer SEmiconductors Italian COrporation

POSEICO SPA
Via Pillea 42-44, 16153 Genova - ITALY
Tel. + 39 010 8599400 - Fax + 39 010 8682006
Sales Office:
Tel. + 39 010 8599400 - Fax + 39 010 8681180

PHASE CONTROL THYRISTOR

AT847

Repetitive voltage up to	**2800 V**
Mean on-state current	**2798 A**
Surge current	**39 kA**

FINAL SPECIFICATION

Sept. 13 - Issue: 5

Symbol	Characteristic	Conditions	Tj [°C]	Value	Unit
BLOCKING					
V_{RRM}	Repetitive peak reverse voltage		125	2800	V
V_{RSM}	Non-repetitive peak reverse voltage		125	2900	V
V_{DRM}	Repetitive peak off-state voltage		125	2800	V
I_{RRM}	Repetitive peak reverse current	V=VRRM	125	200	mA
I_{DRM}	Repetitive peak off-state current	V=VDRM	125	200	mA
CONDUCTING					
$I_{T(AV)}$	Mean on-state current	180° sin, 50 Hz, Th=55°C, double side cooled		2798	A
$I_{T(AV)}$	Mean on-state current	180° sin, 50 Hz, Tc=85°C, double side cooled		2192	A
I_{TSM}	Surge on-state current	sine wave, 10 ms	125	39,2	kA
I^2t	I^2t	without reverse voltage		7683 x1E3	A^2s
V_T	On-state voltage	On-state current = 2100 A	25	1,22	V
$V_{T(TO)}$	Threshold voltage		125	0,85	V
r_T	On-state slope resistance		125	0,175	mohm
SWITCHING					
di/dt	Critical rate of rise of on-state current, min.	From 75% VDRM, gate 10V 5ohm	125	800	A/µs
dv/dt	Critical rate of rise of off-state voltage, min.	Linear ramp up to 75% of VDRM	125	1000	V/µs
td	Gate controlled delay time, typical	VD=100V, gate source 10V, 10 ohm , tr=5 µs	25	2	µs
tq	Circuit commutated turn-off time, typical	dv/dt = 20 V/µs linear up to 75% VDRM		400	µs
Q_{RR}	Reverse recovery charge	di/dt=-20 A/µs, I= 2150 A	125		µC
I_{RR}	Peak reverse recovery current	VR= 50 V			A
I_H	Holding current, typical	VD=5V, gate open circuit	25	500	mA
I_L	Latching current, typical	VD=12V, tp=30µs	25	1000	mA
GATE					
V_{GT}	Gate trigger voltage	VD=12V	25	3,5	V
I_{GT}	Gate trigger current	VD=12V	25	400	mA
V_{GD}	Non-trigger gate voltage, min.	VD=VDRM	125	0,25	V
V_{FGM}	Peak gate voltage (forward)			30	V
I_{FGM}	Peak gate current			10	A
V_{RGM}	Peak gate voltage (reverse)			10	V
P_{GM}	Peak gate power dissipation	Pulse width 100 µs		150	W
P_G	Average gate power dissipation			10	W
MOUNTING					
$R_{th(j-c)}$	Thermal impedance, DC	Junction to case, double side cooled		9,0	°C/kW
$R_{th(c-h)}$	Thermal impedance	Case to heatsink, double side cooled		2,0	°C/kW
T_j	Operating junction temperature			-30 / 125	°C
F	Mounting force			40/ 50	kN
	Mass			1700	g

ORDERING INFORMATION : AT847 S 28

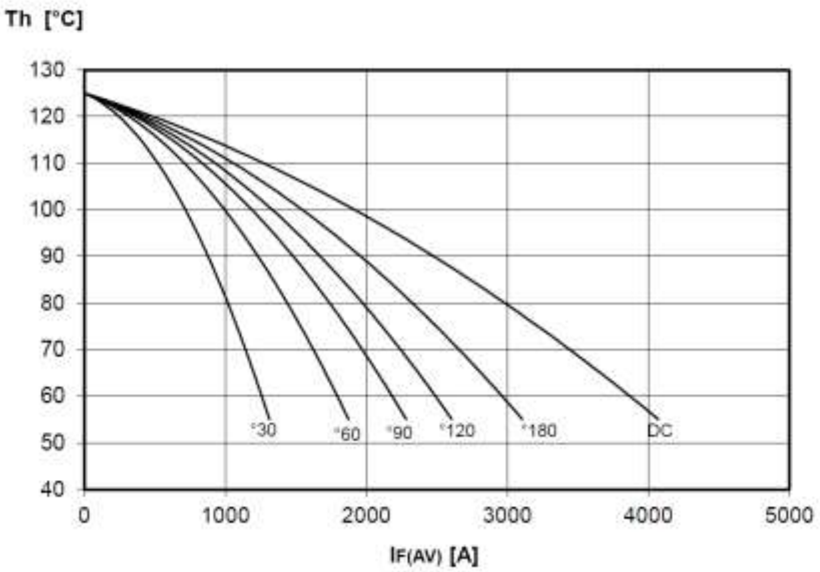
standard specification (S) — VDRM&VRRM/100 (28)

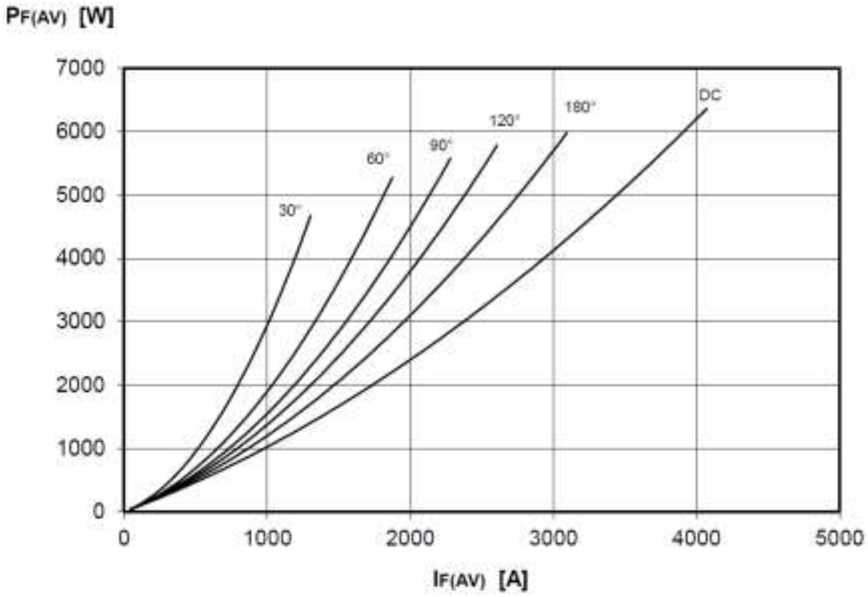
AT847 PHASE CONTROL THYRISTOR

FINAL SPECIFICATION Sept. 13 - Issue: 5

DISSIPATION CHARACTERISTICS

SQUARE WAVE





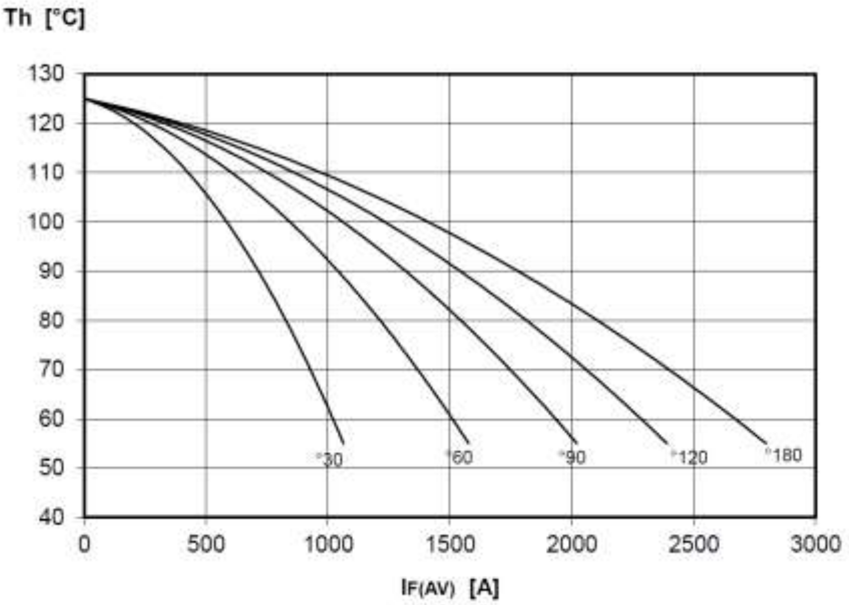
AT847 PHASE CONTROL THYRISTOR

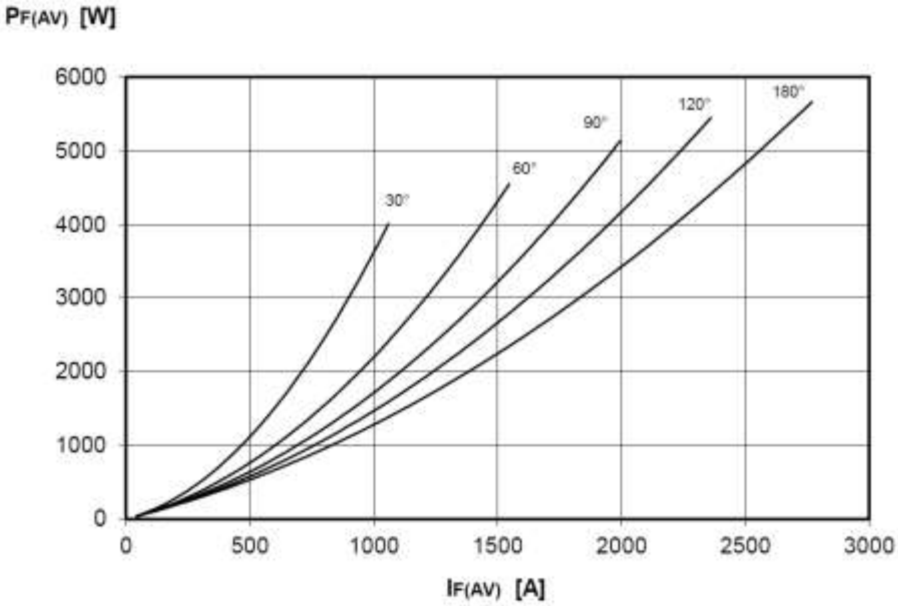
POSEICO

FINAL SPECIFICATION Sept. 13 - Issue: 5

DISSIPATION CHARACTERISTICS

SINE WAVE



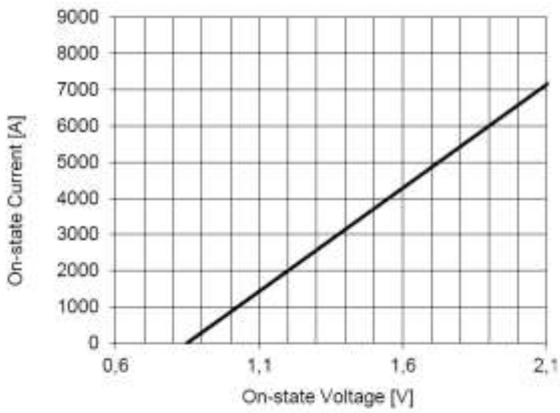


AT847 PHASE CONTROL THYRISTOR

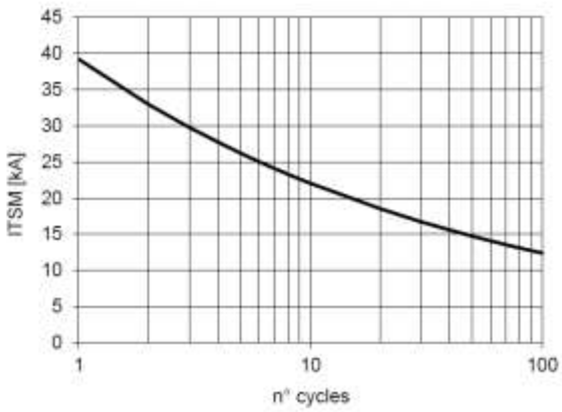
POSEICO

FINAL SPECIFICATION Sept. 13 - Issue: 5

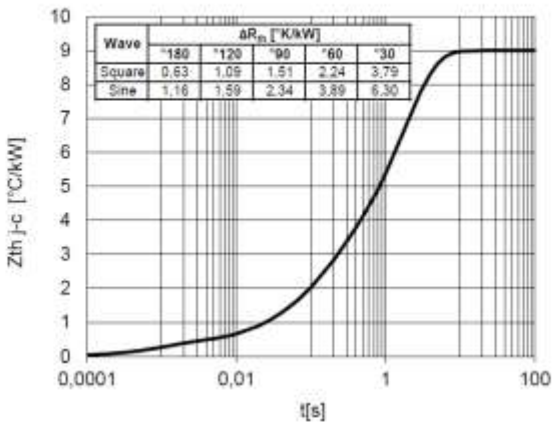
ON-STATE CHARACTERISTIC
Tj = 125 °C

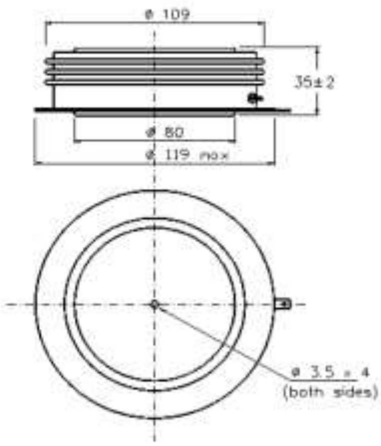


SURGE CHARACTERISTIC
Tj = 125 °C



TRANSIENT THERMAL IMPEDANCE
DOUBLE SIDE COOLED





$$Z_{th\ j-c}(t) = \sum_{i=1}^{n} A_i * \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

i	1	2	3	4
A_i [°C/kW]	6,323	1,815	0,484	0,378
τ_i [s]	1,8	0,16	0,03	0,001

Cathode terminal type DIN 46244 - A 4.8 - 0.8
Gate terminal type AMP 60598 - 1

All the characteristics given in this data sheet are guaranteed only with uniform clamping force, cleaned and lubricated heatsink, surfaces with flatness < .03 mm and roughness < 2 µm.
In the interest of product improvement POSEICO SpA reserves the right to change any data given in this data sheet at any time without previous notice.
If not stated otherwise the maximum value of ratings (simbols over shaded background) and characteristics is reported.

Distributed by

3.6.6 SCR Control System

All the protection and alarm signals are centralised on the JEMA-POSEICO standard Protection Cards W5170 and the DC Link protections PCB W5010. These fast logic PCBs ensures a fast protection of the Power Supply.

The critical alarms are associated and two fibre optics signals are directly sent to the Control System via optic fibres:

- Fast power supply stop: Stops the Power Supply.
- Fast trip breaker: Stops the Power Supply, opens the 18kV Circuit Breaker (out of scope of supply) at the transformer primary side and puts the Power Supply in a secure state, ready to be discharged and earthed if required.

Different board are used to manage and firing the rectifier.

3.6.7 Thyristors Firing Circuit

The thyristors firing signals are generated in the Rectifier Control System by a set of drivers which provide duly synchronised 12 V pulses. These electrical signals are converted into light by the W3380 JEMA-POSEICO standard PCB, and transmitted to the Power Cabinet through silica optic fibres. Once they reach this point they get converted into electrical signal again (W3390 JEMA-POSEICO standard card), and are amplified to 40 V/4 A (W3400 JEMA-POSEICO standard card) to reach the thyristors firing level. Before being applied to the thyristor, each firing signal is moved through an isolation voltage transformer (W3410 JEMA-POSEICO standard PCB).

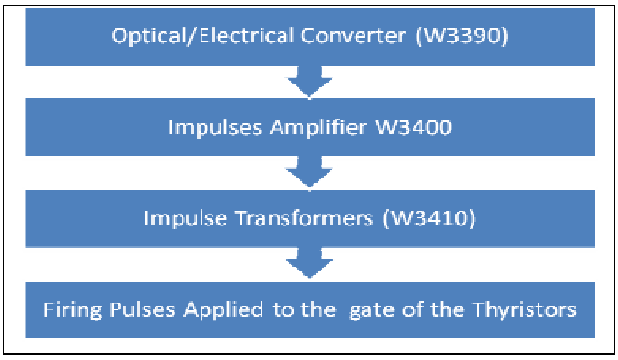


Fig. 5 – Simplified Flow chart of Firing circuit

3.6.8 Optical to electrical signal interface circuit

The firing pulses transmitted by optical fibres from the control unit, reach the power unit via the W3390 interfaces (one per 6 pulse bridge). Here the light signals are converted into electrical signals. Each of these W3390 interfaces has 4x40 pins ribbon wire cable output connector for the W3400 pulse amplifier circuit which is always located very near. These interface boards receive a +15 VDC supply to power their own electronic systems, and a +40 VDC to power the W3400 pulse amplification circuits via a 24-pin flat wire cable. Moreover, this W3390 circuit provides a diagnosis of any failures arising during the optical/electronic conversion, i.e., failures at the Power Supply, W3400 Pulse Amplifier Interface and the W3410 Auxiliary Firing Interface.

3.6.9 Pulse Amplification Interface Circuit

This interface receives low-power electrical firing signals coming from the W3390 through a 40-pin flat wire cable, for a single bridge or two antiparallel bridges. Here the amplification takes place up to 40V/4A, and the signals are ready to supply the thyristor gate. This interface also receives the required power supply to operate at +40 VDC from the W3390 type interface via 40-pin flat wire cable.

3.6.10 Auxiliary Firing Interface Circuit

All the 6 amplified firing signals corresponding to one bridge feed 6 pulse transformers, located on this card. Signals arrive to this circuit from the W3400 via a 40-pin flat wire cable. From the W3410, they will be directly wired to the thyristor's terminals. Each interface has 6 yellow LEDs, which show if firing pulses are being applied.

3.6.11 Auxiliary Power Supply

There is a power supply for every rectifier bridge or both antiparallel bridges, to supply the +40 V and +15 V required for processing the optical fibre signals coming from the control unit. The power supply to the various interface circuits is implemented via 24-pin flat wire cable. The supply for this interface comes from an insulation transformer for auxiliary voltage.

3.6.12 Heat-sink Data Sheets

In order to obtains the maximum of modularity and to reduce cost of spare parts and maintenance management for all Power Supplies only 1 type of heat-sink has been used, bilateral water cooled type that included also the output connection to + and – or to 3 phases bars. In this type of solution the number of contacts between different connections has been reduced to minimum. This solution was made possible by the technology POSEICO of water heat-sink construction, which allows easy design of reliable and customized aluminium heat-sink. The details of performance of the water cooling heat-sink POSEICO type AWCH-L320W160T28C are reported in next the two pages.

POSEICO

POSEICO SPA

POwer SEmiconductors Italian COrporation

POSEICO SPA
Via Pillea 42-44, 16153 Genova - ITALY
Tel. + 39 010 8599400 - Fax + 39 010 8682006
Sales Office:
Tel. + 39 010 8599400 - Fax + 39 010 8681180

WATER COOLER FOR PRESS-PACK AND MODULE POWER SEMICONDUCTORS

AWCH-L320W160T28C

Thermal Resistance	**4.0 °C / kW**
Max. Operating Temperature	**85 °C**
Typical Cooling Flow Rate	**2 ÷ 10 l / min**

TARGET SPECIFICATION

set 13 - ISSUE : 0

Symbol	Characteristic	Conditions		Value	Unit
THERMAL					
R_{th}	Thermal resistance heatsink to fluid	Double side cooled, Q= 5 l/min, Contact area = 7850 mm^2 (ϕ=100mm)		4.0	°C / kW
R_{th}	Thermal resistance heatsink to fluid	Single side cooled, Q= 5 l/min, Contact area = 7850 mm^2 (ϕ=100mm)		5.9	°C / kW
T_{min}	Minimum temperature of inlet fluid			-30	°C
T_{typ}	Typical temperature of inlet fluid			30÷60	°C
T_{max}	Maximum operating temperature	With deionized water		85	°C
MECHANICAL AND ENVIRONMENTAL					
Q	Cooling flow rate			2 / 10	l / min
ΔP_{typ}	Typical pressure drop	Q = 5 l/min; T= 25°C		210	mbar
ΔP_{max}	Maximum pressure drop	Q = 5 l/min; T= 25°C		260	mbar
$P_{i\,max}$	Maximum operating inner pressure			12	bar
	Surface planarity		≤	0.025	mm
R_a	Surface roughness		≤	1.6	µm
T_s	Storage temperature			-40 / 100	°C
	Mass			3800	g

DESCRIPTION

- Aluminum water coolers, suitable to accept press-pack devices, dissipating up to 2500 W per side (2500 + 2500 in total), with a contact area up to a diameter of 125mm
- Suitable for deionized water cooling fluid

ORDERING INFORMATION: AWCH-L320W160T28C

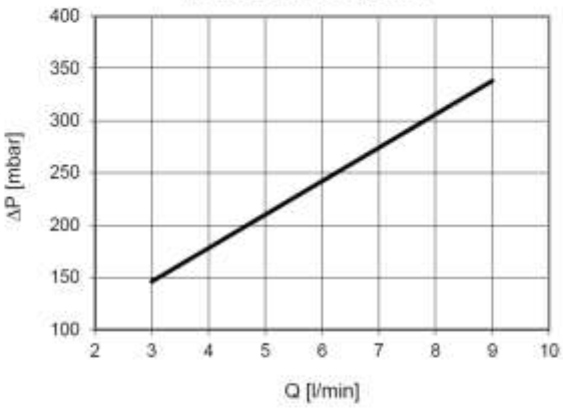
If a nipple different from the reported in the standard drawing is required add the Z-number as shown in the connection list **(see pag. 25):**

Example: AWCH-L320W160T28C-Z1

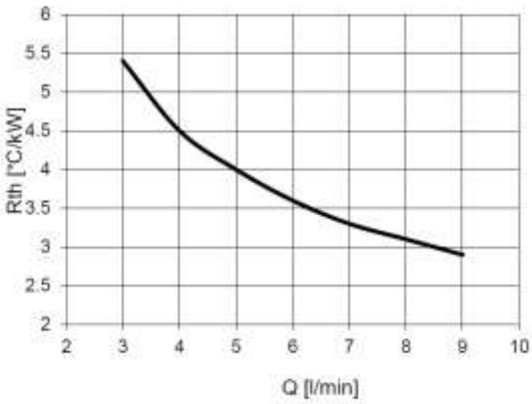
AWCH-L320W160T28C	***WATER COOLER FOR PRESS-PACK AND MODULE POWER SEMICONDUCTORS***	POSEICO

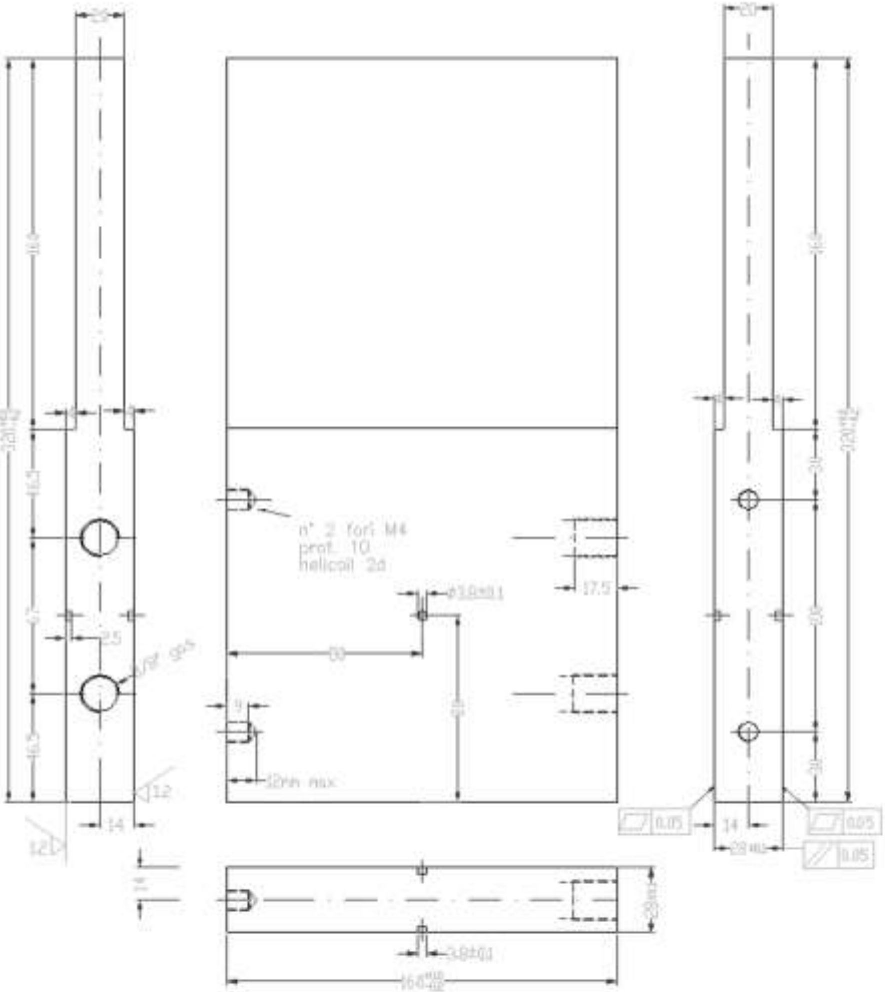
TARGET SPECIFICATION set 13 - ISSUE : 0

TYPICAL PRESSURE DROP



DOUBLE SIDE THERMAL RESISTANCE





All the characteristics given in this data sheet are guaranteed only with uniform clamping force, cleaned and lubricated contact surfaces with flatness < 0.05 mm and roughness < 1,6 µm.
In the interest of product improvement POSEICO reserves the right to change any data given in this data sheet at any time without previous notice.
If not stated otherwise the maximum value of ratings (simbols over shaded background) and characteristics is reported.

3.6.13 Fuses Data Sheet

They are defined on base of the results reported in the table 14.

Table 14 – PS Fuses Design.

PS Fuses Design													Alternative solution	
		Converter type			CS1	CS2	CS3	CS4	EF1	EF6	FPPC1	FPPC2	FPPC1	FPPC2
Converter		Q.ty Bidirectional			2	2	2	2	1	1				
Converter		Q.ty Unidirectional							1	1	4	4	4	4
Converter		Nominal AC Voltage		V	803,5	960	960	803,5	803,5	803,5	390	390	780	780
Device	N° of Parallel Device (Thyristor)				2	2	2	2	2	2	1	1	1	1
Device	Withstand Steady State Nominal Current	Maximum Equivalent RMS Current		A	3637	3637	3637	3637	3637	3637	2887	2887	1518	1518
Device	Withstand Steady State Nominal Current	Duty/cycle	t_{ON}/T	s/s	220/1800	220/1800	220/1800	220/1800	220/1800	220/1800	140/1800	140/1800	140/1800	140/1800
Device	Withstand Short Circuit after Smoothing Reactor	Starting Maximum Current	I_0	A	6300	6300	6300	6300	6300	6300	5250	5250	2625	2625
Device	Withstand Short Circuit after Smoothing Reactor	Linear Decay to 0 Time	t_0	s	1,18	0,41	0,41	1,18	1,18	1,18	0,48	0,48	0,15	0,15
Device	Withstand Short Circuit after Smoothing Reactor	Maximum Sinusoidal Peak-to-Peak Overcurrent	$I_1 - I_0$	A	5720	6834	6834	5720	5720	5720	4627	4627	9255	9255
Device	NotWithstand Short Circuit before Smoothing Reactor	Minimum Peak Current	Half sine Wave 17 ms pulse duration	kA	86,3	31,4	31,4	86,3	86,3	86,3	47,1	47,1	23,5	23,5
Device	NotWithstand Short Circuit before Smoothing Reactor	I^2t of Device to be protected		MA^2s	28,13	23,12	23,12	28,13	28,13	28,13	18,00	18,00	7,68	7,68
Device	Short circuit due to Component Failure	Maximum Peak Current	Half sine Wave 17 ms pulse duration	kA	308,7	112,5	112,5	308,7	308,7	308,7	67,4	67,4	33,7	33,7
Device	Short circuit due to Component Failure	Maximum Pre-arc time		ms	1,97	7,36	7,36	1,97	1,97	1,97	7,04	7,04	-	-
Device	Short circuit due to Component Failure	Maximum Peak Pre-arc Current		kA	110	110	110	110	110	110	65	65	-	-
	Short circuit due to Component Failure	Maximum I^2t		MA^2s	40,50	40,50	40,50	40,50	40,50	40,50	15,13	15,13	15,13	15,13
	N° of Fuse for converter				24	24	24	24	24	24	24	24	24	24

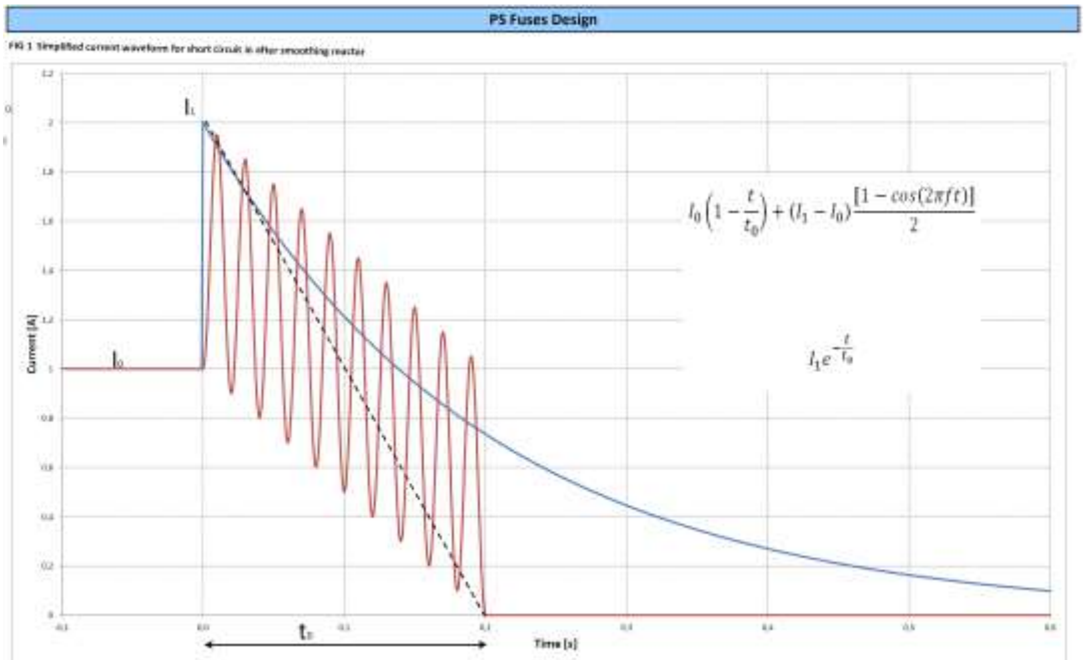


Fig. 6 – Waveform of short-circuit current after smoothing reactor

3.6.14 RC Protection

Each thyristor is protected by its snubber (an RC circuit in parallel) to limit the *dV/dt*, which appears during semiconductor commutations. The snubbers have been selected with the following initial expected values, to be confirmed yet:

- $R_{snubber}$: 2 Ohm.
- $C_{snubber}$: 10µF

3.6.15 Thermal protection

Each rectifier leg will have a temperature sensor at the heat-sink in worse thermal conditions. The sensor will produce a temperature high alarm level at 60°C. The status of these thermostats are permanently controlled and monitored by the control system.

3.6.16 Filter reactor specification

An interphase reactor will be included at the output of every 6-pulse bridge in order limit the interphase current and/or the circulating current during current direction change over. Thus, there are four filter reactors per rectifier. The characteristics of the reactors are set out in the following table.

Table 15 – Characteristics of the reactors.

Rated Inductance	1.4mH
Rated Current (Ieff)	1800ADC continuous
Ripple Current	100 App
Ripple frequency	300 Hz
Cooling	Natural air
Series resistance (I1 – I2)	6.1 mΩ
Insultation voltage	10kVAC 1 min
Exit bars	Aluminium
Protection index	IP00
Overall dimensions L x D x H	1120 x 1160 x 1620 mm
Weight	630 kg

The final design of those reactors will take place during the equipment design phase. The selection of their final characteristics, coupled reactors, iron core or air, saturable or linear, will take place taking in account the intermittent current operation limit, additional losses in the thyristors, etc. Detailed simulations will be carried out to demonstrate the correct operation of the bridges mainly during the current direction change over.

3.6.17 PS Electrical diagrams

In the next figures, the following electrical diagrams for each PS are showed:

- Circuit Configuration CS1
- Circuit Configuration CS2 – CS3
- Circuit Configuration CS4
- Circuit Configuration EF1
- Circuit Configuration EF6
- Circuit Configuration FPPC1 – FPPC2 Parallel
- Circuit Configuration FPPC1 – FPPC2 Series

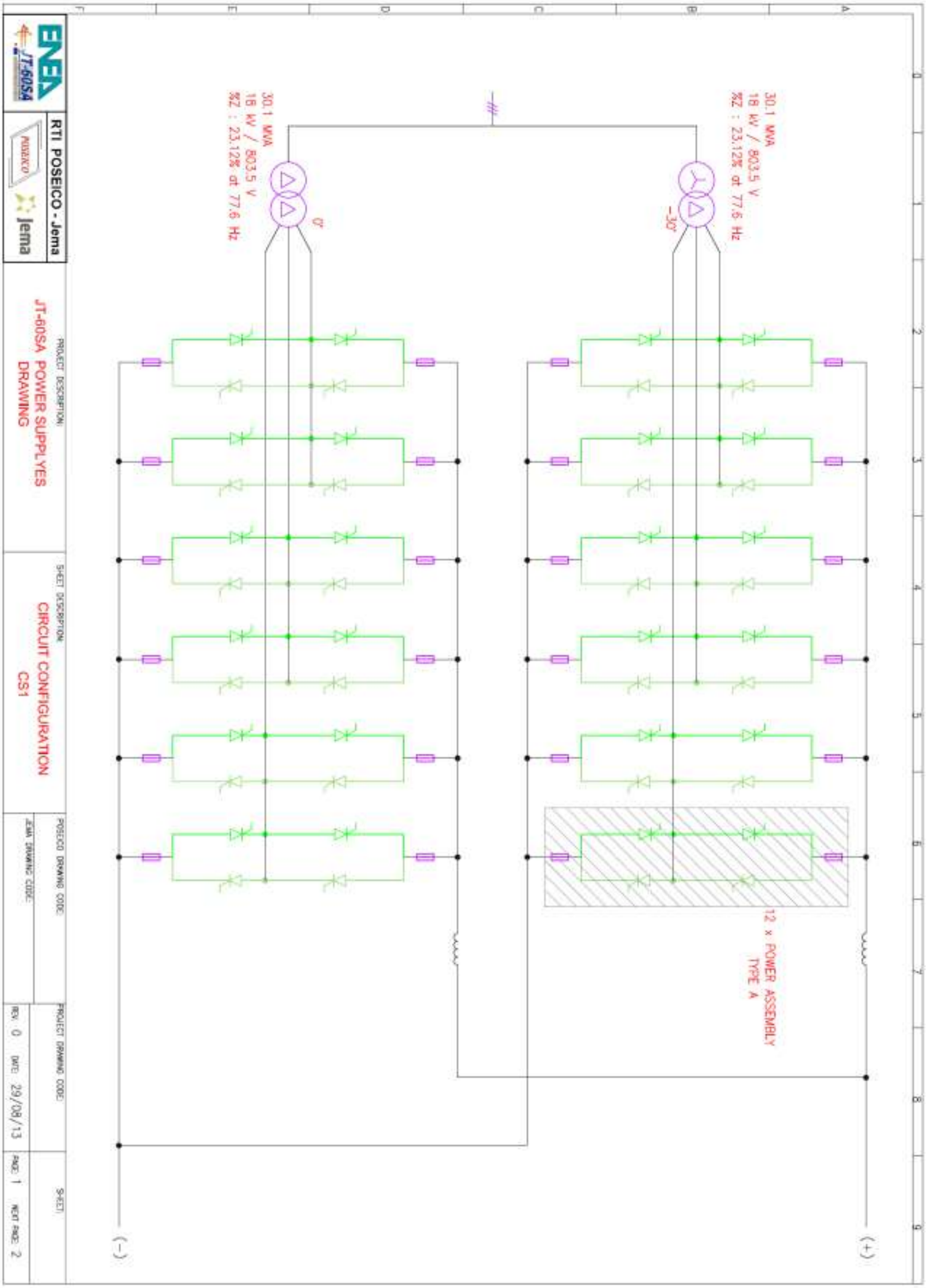


Fig. 7 – Circuit configuration CS1

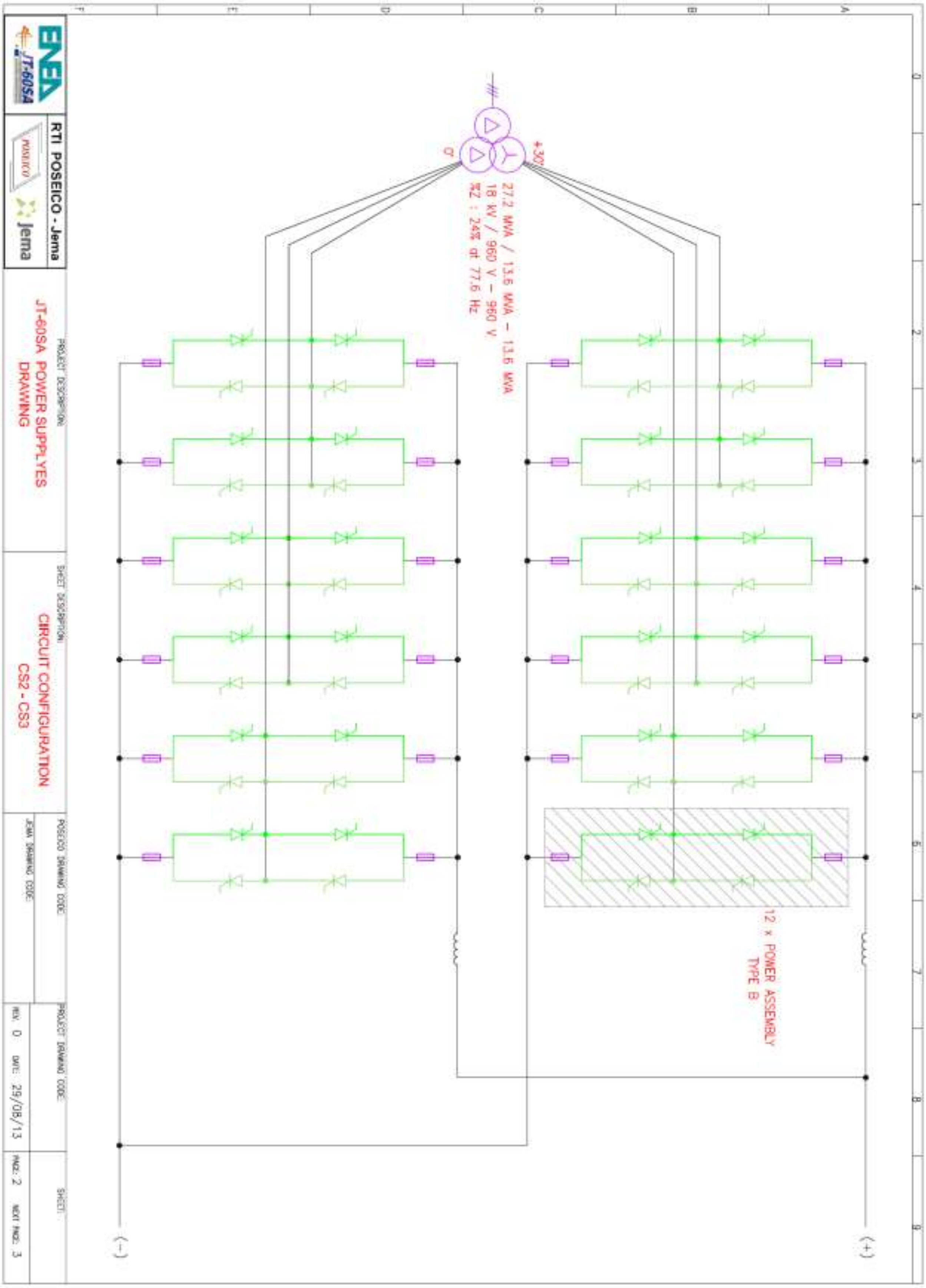


Fig. 8 – Circuit configuration CS2 & CS3

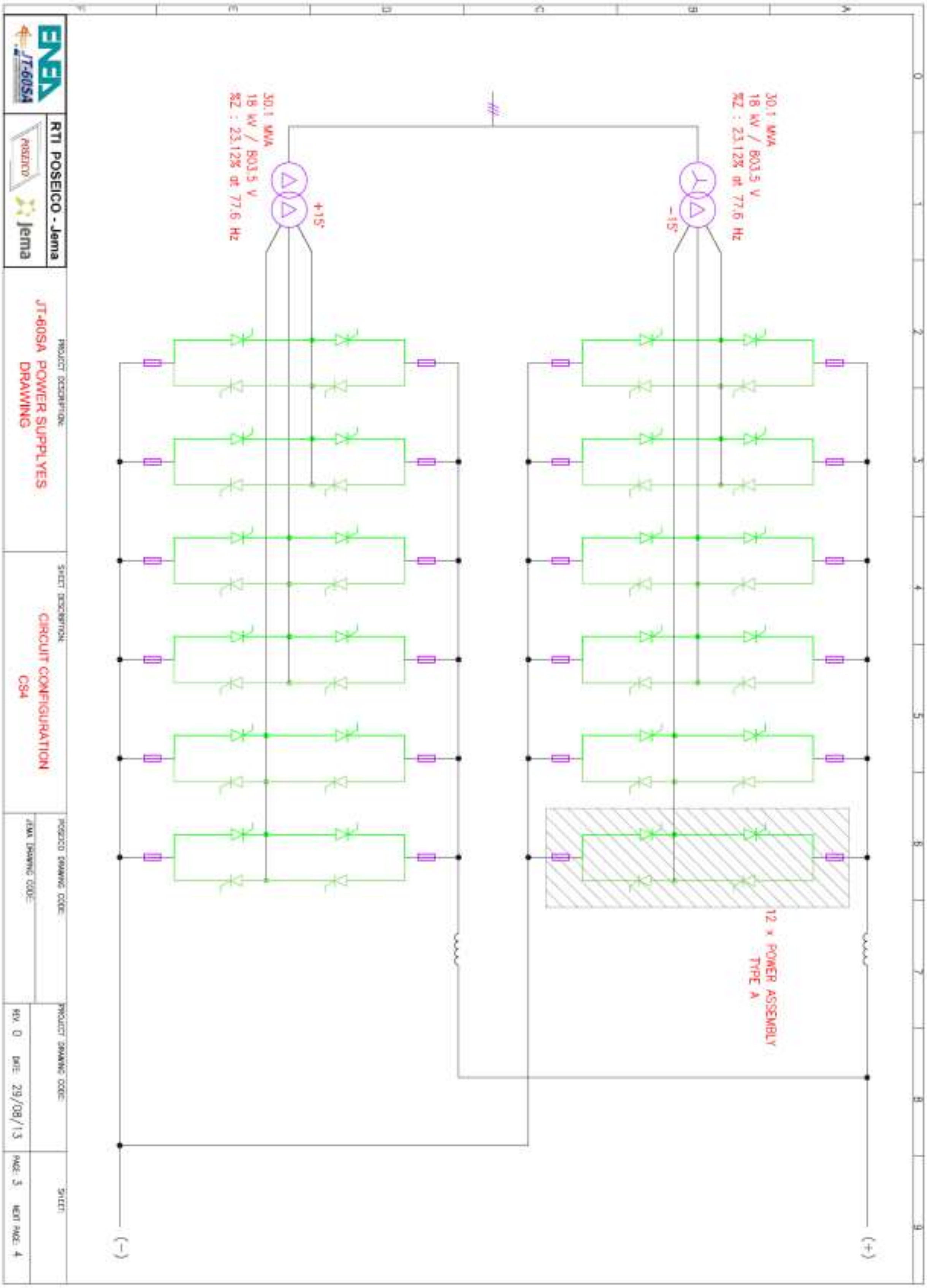


Fig. 9 – Circuit configuration CS4

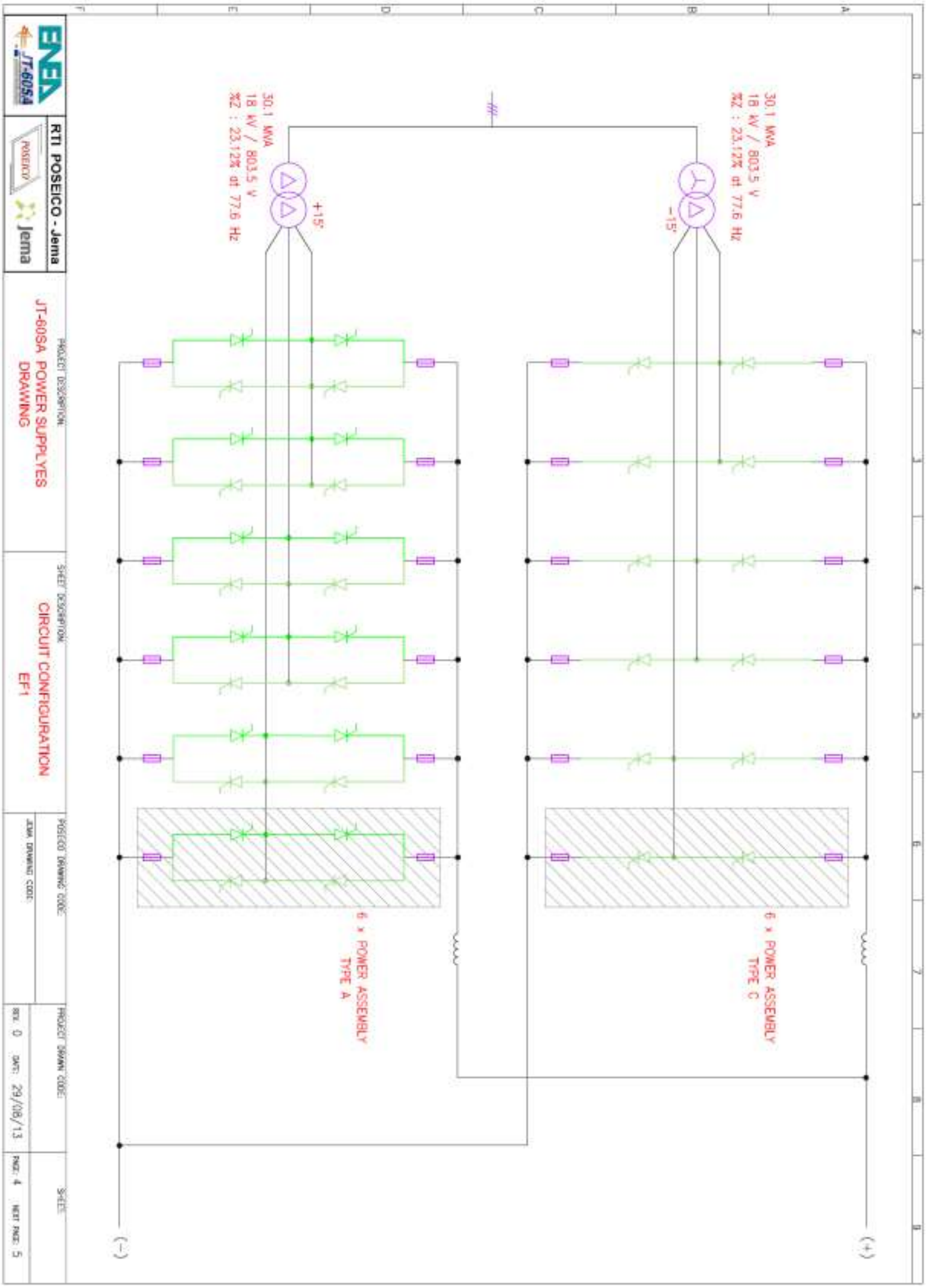


Fig. 10 – Circuit configuration EF1

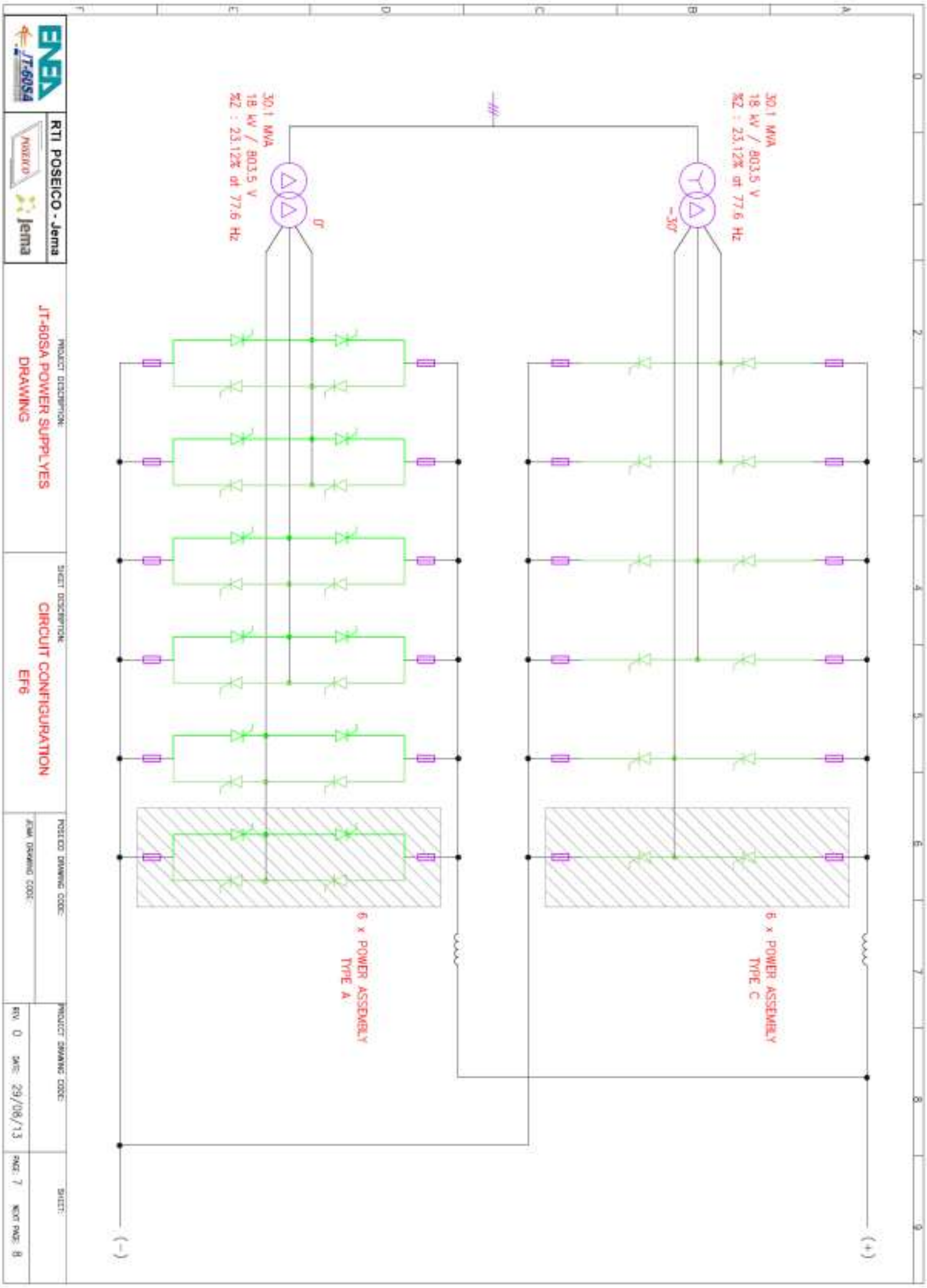


Fig. 11 – Circuit configuration EF6

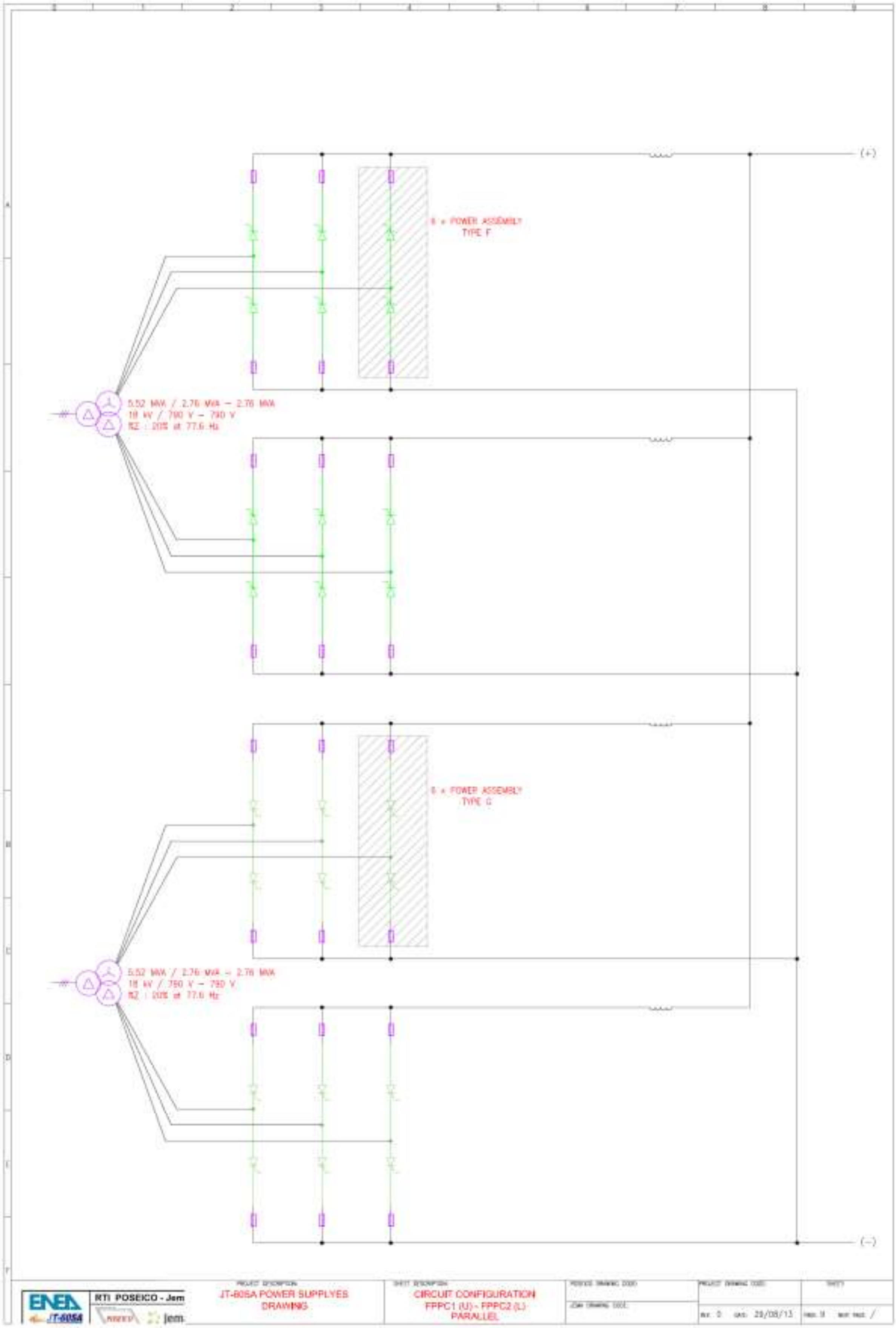


Fig. 12 – Circuit configuration FPPCs (parallel)

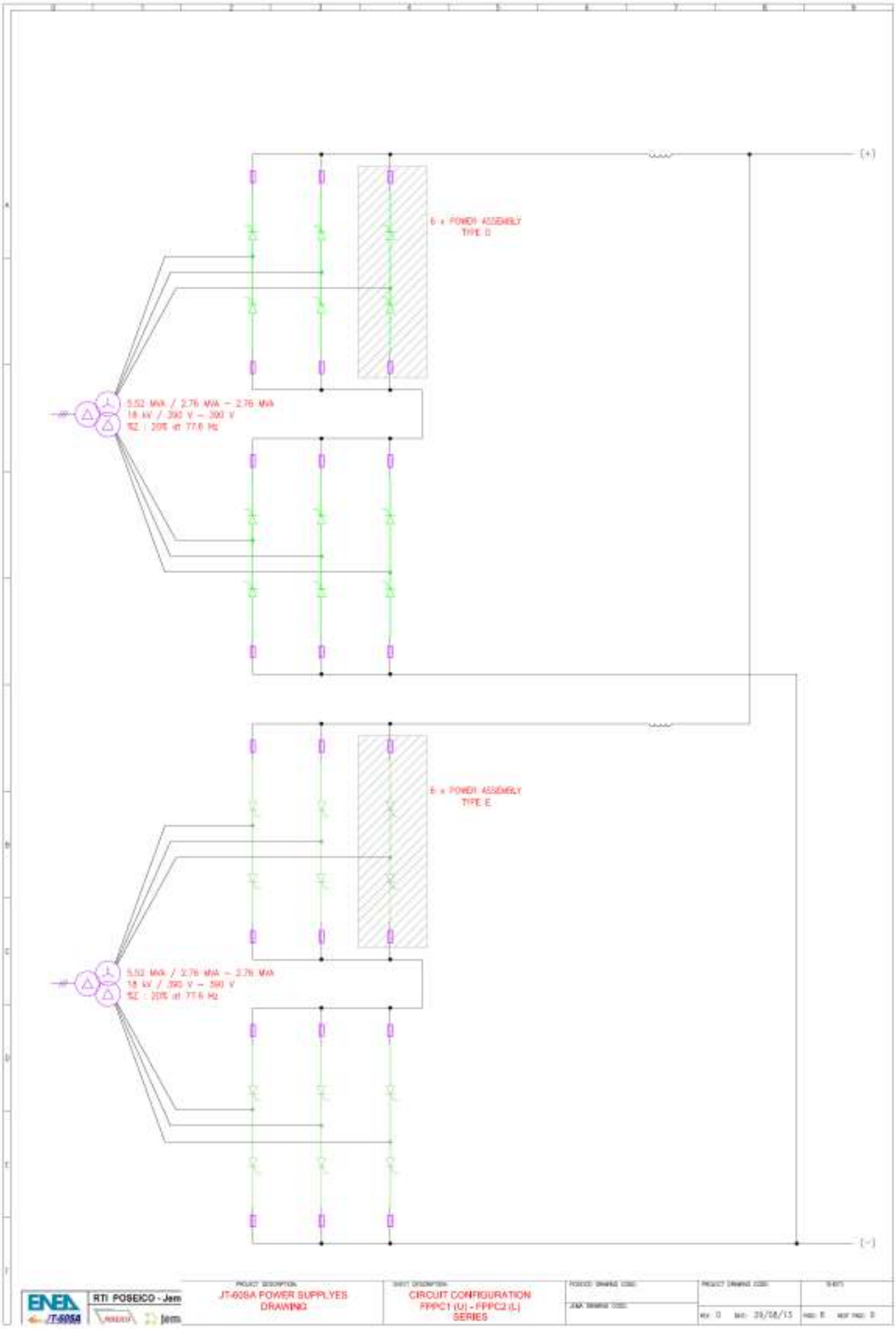


Fig. 13 – Circuit configuration FPPCs (series)

3.6.18 Power Assemblies layout drawings

In the next figures, the following drawings for the different Power Assemblies

- Power assembly type A
- Power assembly type B
- Power assembly type C
- Power assembly type D
- Power assembly type E
- Power assembly type F
- Power assembly type G

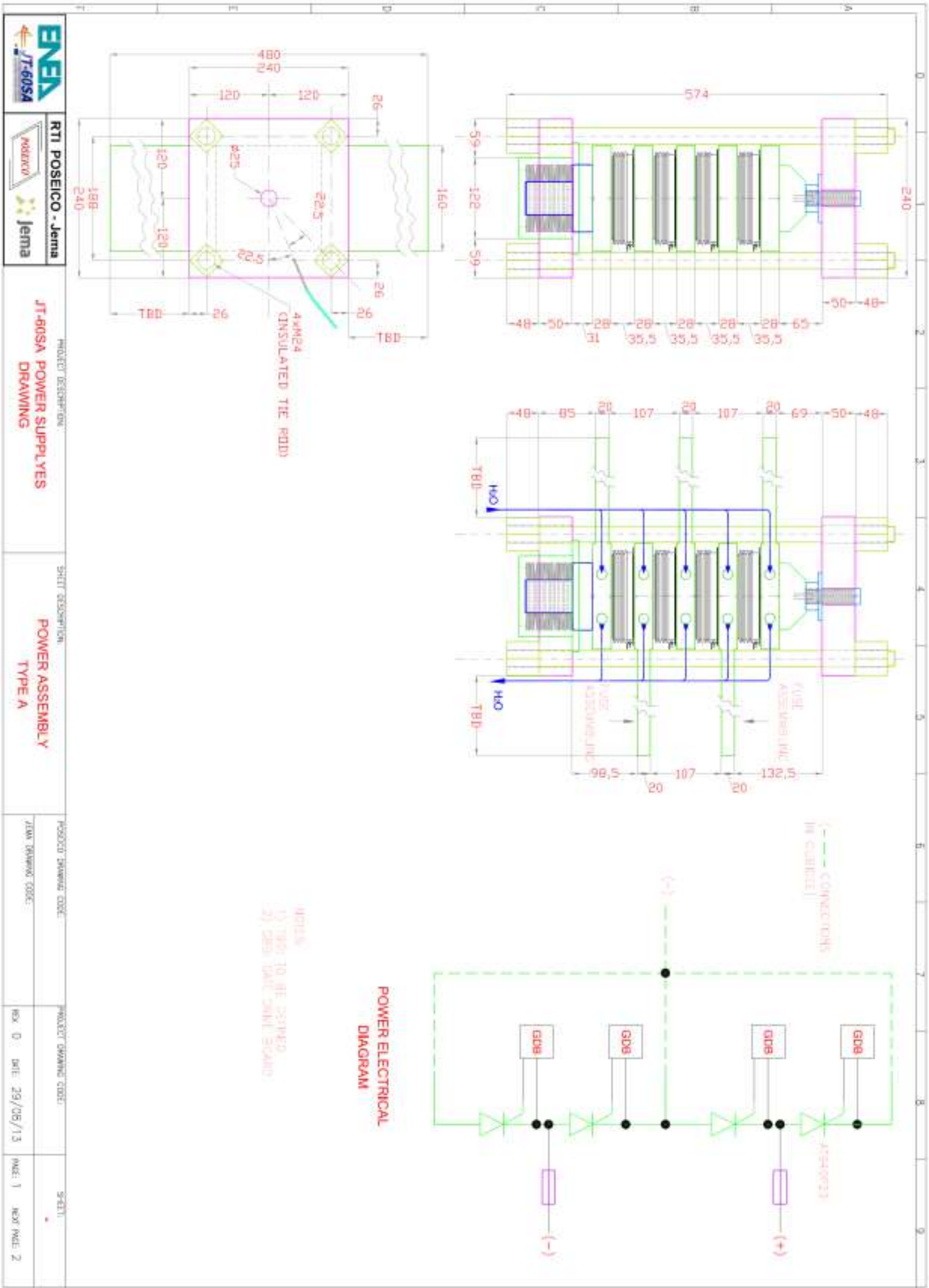


Fig. 14 – Power assembly type A

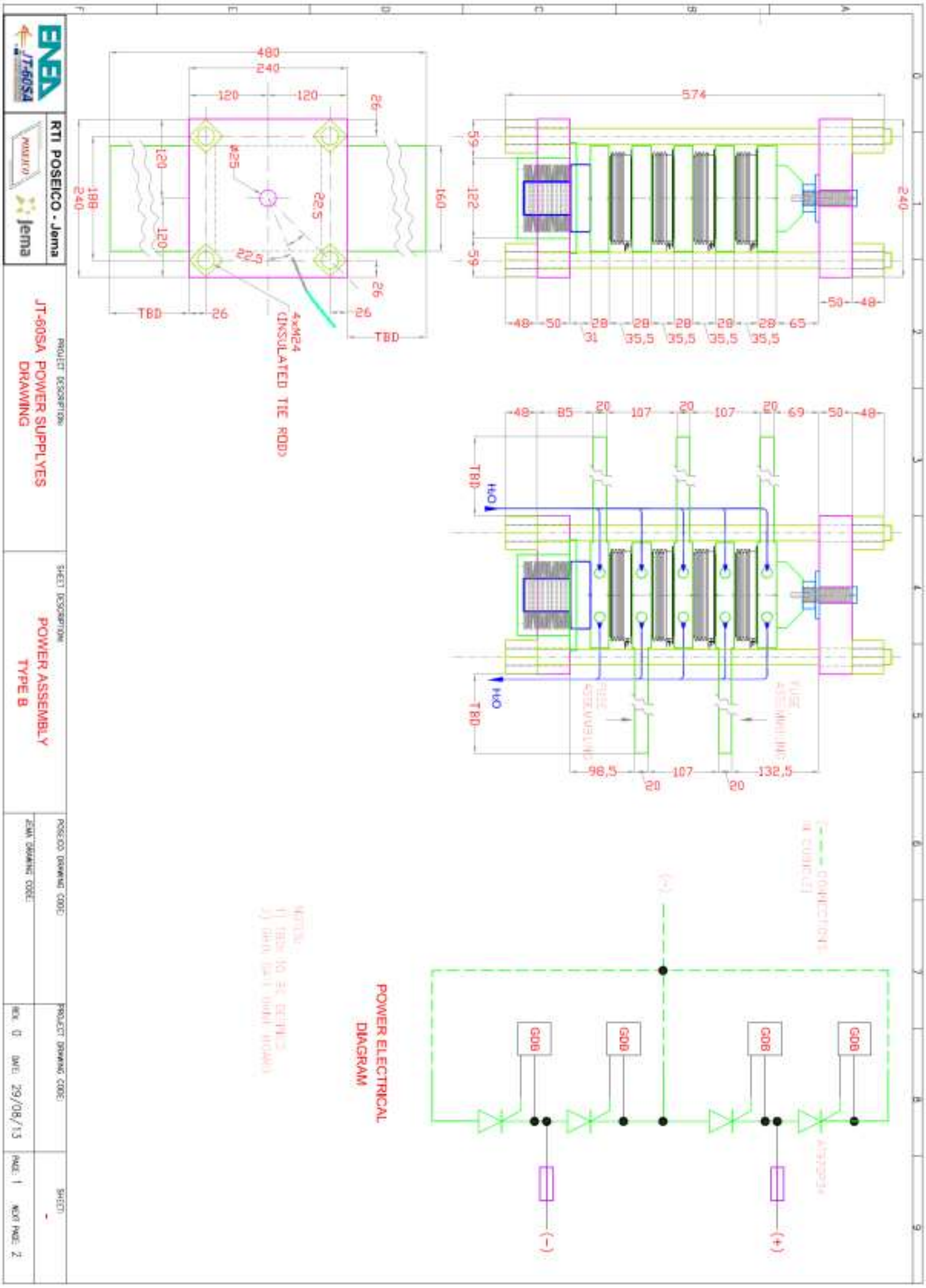


Fig. 15 – Power assembly type B

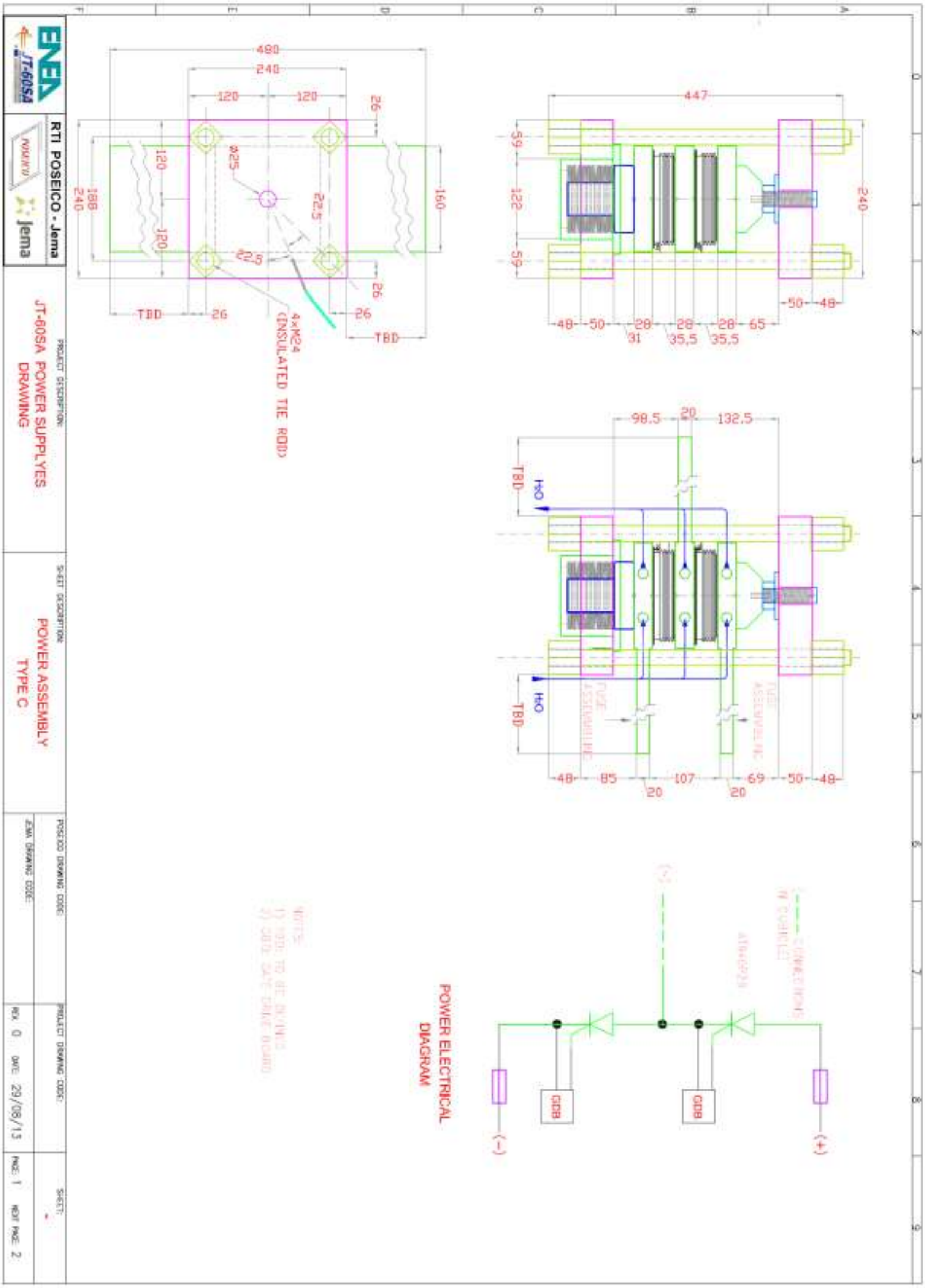


Fig. 16 – Power assembly type C

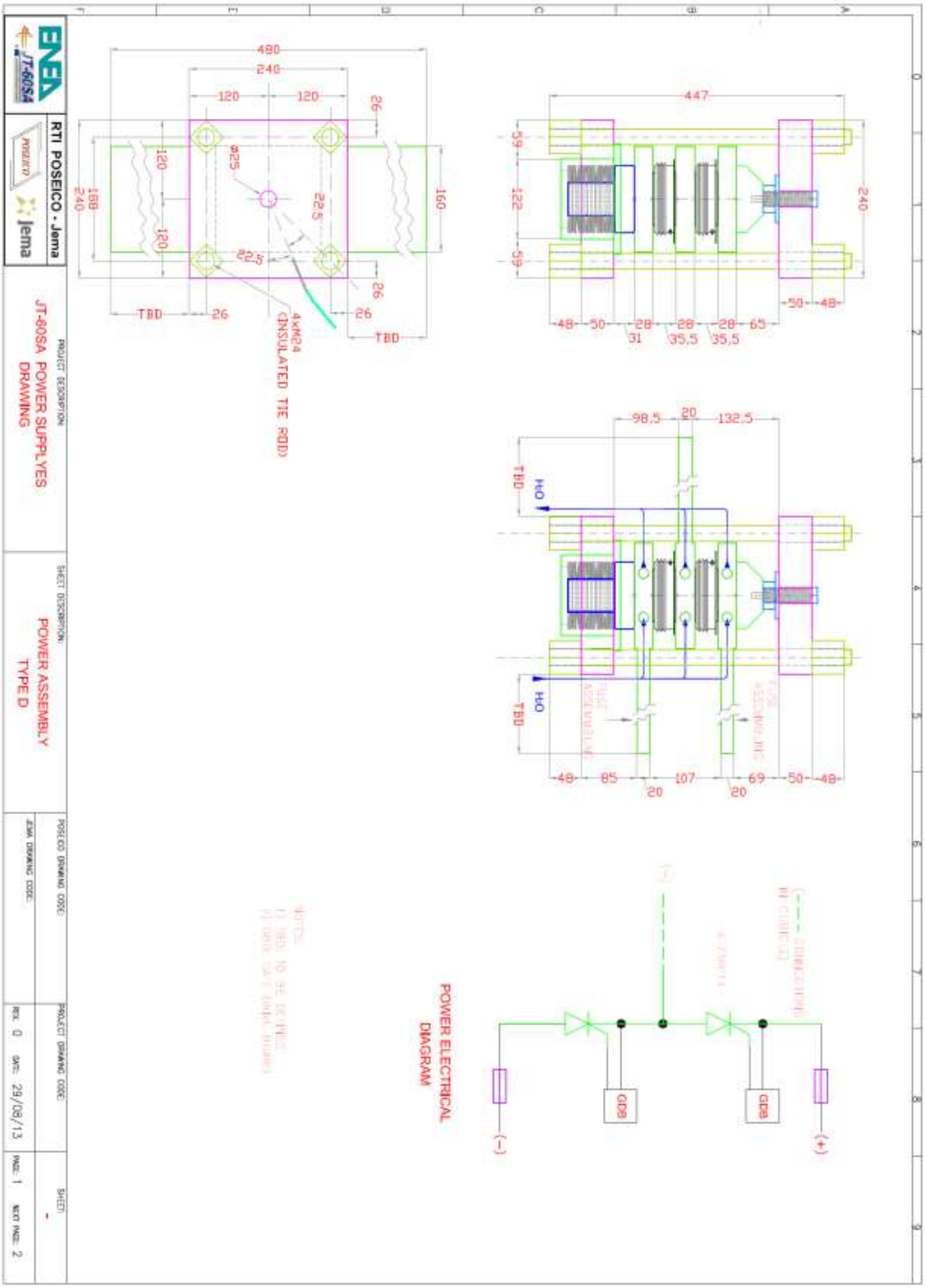


Fig. 17 – Power assembly type D

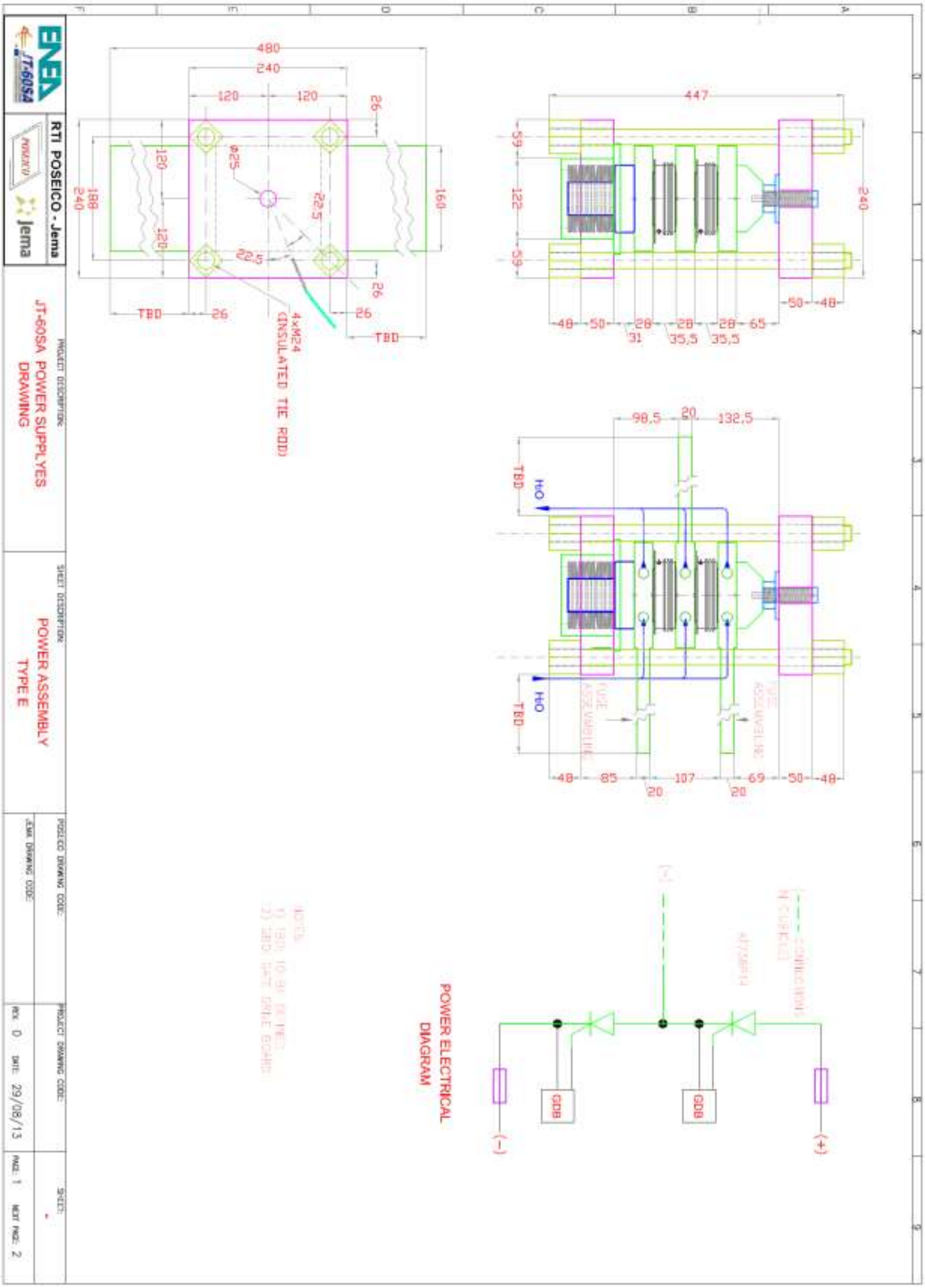


Fig. 18 – Power assembly type E

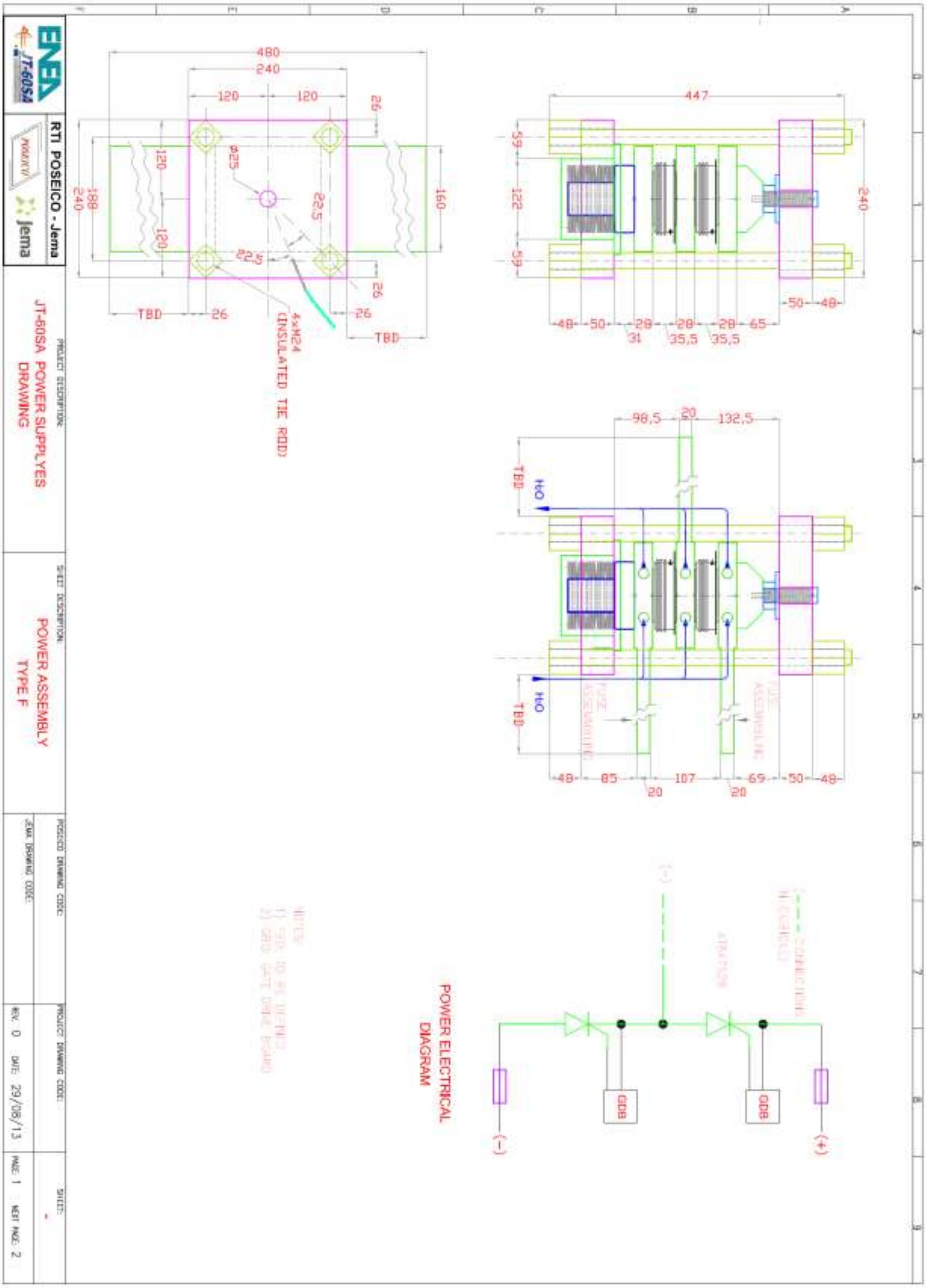


Fig. 19 – Power assembly type F

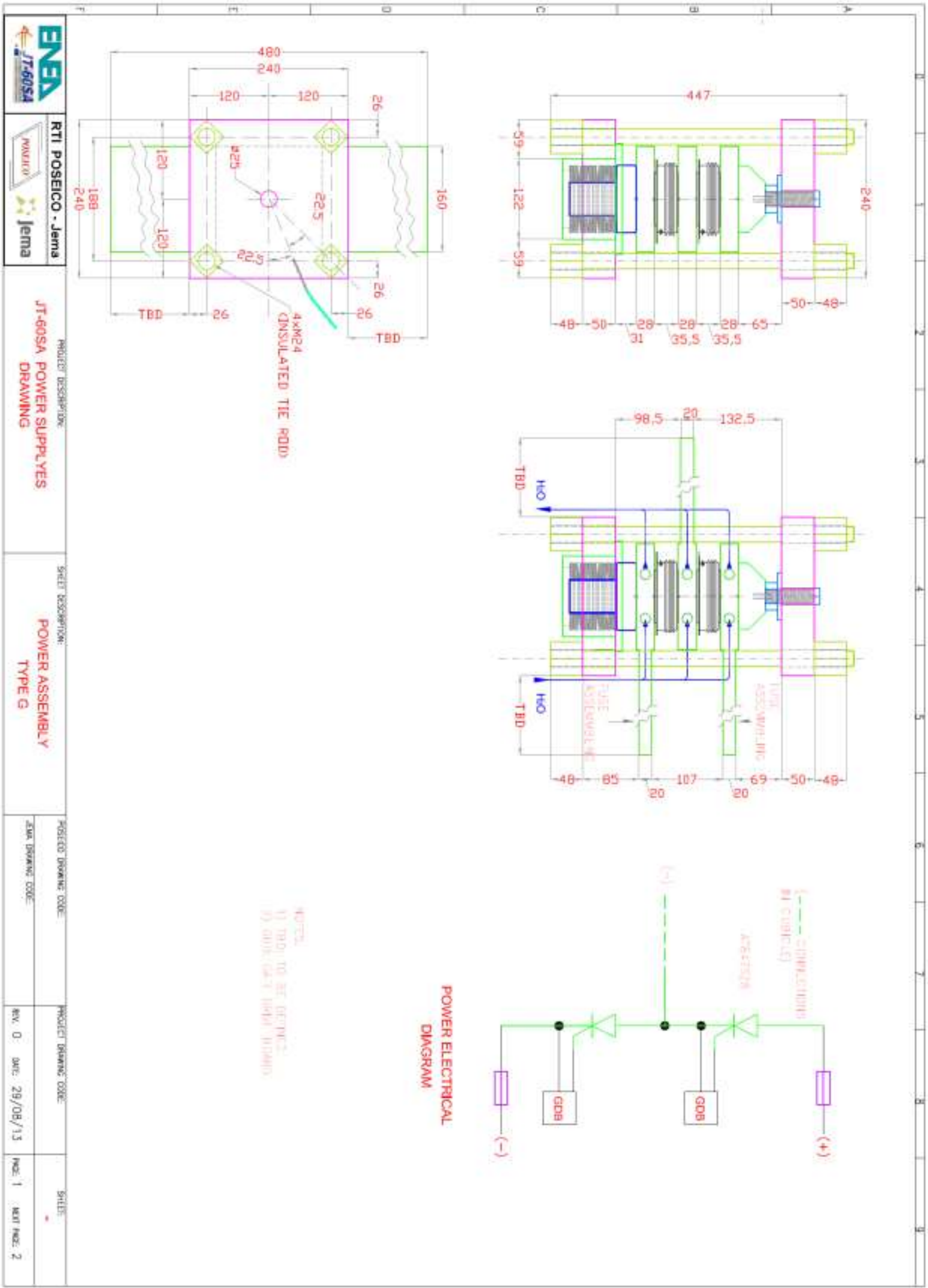


Fig. 20 – Power assembly type G

3.6.19 Validation and simulation results

The simulation was used in the project as a tool for verifying the PS calculations realized in the document. In particular, the following activities were carried out during the simulation phase

- PSIM Simulation of the fault currents in 3 different fault conditions;
- PSIM Simulation for every PS, of thyristors junction temperature during the operative – nominal condition and for the condition of short circuit after inductor;

The Method used and results are reported in the documents.

3.6.20 Earth Resistors

The output of the power supplies will have earth resistors in order to provide a grounding protection. A 1kOhm resistance between positive polarity and earth, and another 1kOhm resistance between negative polarity and earth are expected. The function to create a floating potential between the DC link bars obeys to the principle of referring all systems components to a common potential, i.e. to Ground. Consequently a single reference of the working potential is used both for measurements and for safety. In this particular system the common potential is connected to Ground (earth).

4 Conclusioni

Il presente documento riporta la descrizione delle attività di progettazione degli 8 sistemi di alimentazione elettrica sperimentali e non convenzionali per l'esperimento internazionale JT-60SA. Il contratto per la fornitura di otto Alimentatori e sei Trasformatori per JT- 60SA PFC PS (CS1 , CS2 , CS3 , CS4 , EF1 e EF6 PS e le due FPPC PS) è stato assegnato da ENEA al fornitore industriale POSEICO - JEMA in RTI.
Gli aspetti specifici del progetto sono stati definiti durante la fase 1 di progettazione di dettaglio, che prevede come risultato finale:

- Fase 1a: dimensionamento esecutivo dei trasformatori;
- Fase 1b: redazione del documento relativo all'ingegnerizzazione con selezione della componentistica industriale dei sistemi di alimentazione.

Il presente documento mostra le evidenze di questa fase di progettazione con il dimensionamento esecutivo dei trasformatori e la redazione del documento relativo all'ingegnerizzazione con selezione della componentistica industriale dei sistemi di alimentazione. La fase di progettazione è stata basata su criteri di conformità alle specifiche tecniche, modularità, affidabilità, manutenibilità, mitigazione del rischio e analisi dei guasti. Infatti, come può essere facilmente notato, per tutte le applicazioni sono richieste solo 4 tipologie di tiristori e un numero limitato di unità di 'Power Assembly'. Queste soluzioni progettuali hanno una ricaduta diretta sia in termini di migliore manutenibilità sia in termini di minor costo delle parti di ricambio.

5 Riferimenti bibliografici

1. AA., VV., "PID Plant Integration Document (V3.3)" Broader Approach Satellite Tokamak Programme BA_D_222UJYv3.3.
2. AA., VV., POSEICO-JEMA, "Transformers Design Report – (TCS2, TCS3, TFPPC1, TFPPC2) – Phase 1A, Issue: 00 on 26.09.2013, Reference: RT-JT60PS-PJ-002.
3. AA., VV., POSEICO-JEMA, "Power Supplies Design Report - (CS1, CS2, CS3, CS4, EF1, EF2, FPPC1, FPPC2) – Phase 1B, Issue: 00 on 26.09.2013, Reference: RT-JT60PS-PJ-001.
4. AA., VV., "POSEICO/JEMA QUALITY PLAN for the Procurement of 8 Super Conducting Magnet Power Supply (SCMPS) systems of the JT-60SA Tokamak", Issue: 00 on 26.09.2013, Reference: QP-JT60PS-PJ-001.
5. A. Lampasi, F. Starace, "Technical Specifications for the ENEA SCMPS Call for Tender", ENEA ID: SPT-JT60PS-01.
6. P. Zito, P. Costa, A. Lampasi, "Management and Quality Specifications for the ENEA SCMPS Industrial Supplier ", ENEA ID: MQS-JT60PS-01.
7. A. Coletti, "Withstand test voltage to ground", ref. BA_D_228FVF v.4.0 - 29/04/2011.

6 Abbreviazioni ed acronimi

Acronym	Term	Definition
AC	Alternating Current	–
AoC	Agreement of Collaboration	Framework between F4E and VC-DI to reinsure its commitments towards JAEA under the Procurement Arrangements
–	Annex	Drawings and documents considered as integrant parts of this Technical Specifications and provided to the potential ISs during the Call for Tender
APS	Auxiliary Power Supply	Auxiliary power supply provided by JAEA at Naka Site
BA	Broader Approach	Agreement between Japan Government and the European Atomic Energy Community for the joint implementation of the activities in the field of fusion energy research
BOD	Break-Over Diode	Device supporting the CB protection
BPS	By-Pass Switch	Electromechanical device of a SNU
CB, CBU	Crowbar (Unit)	Electrical circuit used to prevent an overvoltage of a power supply
CRL	Current Reversing Link	Links inserted in the PSs to reverse the polarity of the magnetic field
CS	Central Solenoid	Nb_3Sn conductor consisting of 4 independent modules
–	Customer	VC-DI responsible for handling financially and legally the Procurement of its in-kind contributions: for this Procurement, the Customer is ENEA
DC	Direct Current	–
DDP	Detailed Design Phase	In this phase, the IS shall detail the technical solutions selected to comply with the requirements
DEMO	DEMO	DEMOnstration Power Plant intended to build upon the success of ITER
DMS	Document Management System	BA Document Management System (also known as IDM)
EF	Equilibrium Field	Equilibrium Field (coil)
EMC	Electromagnetic Compatibility	Correct operation of different objects in the same electromagnetic environment
ENEA	ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
F4E	Fusion for Energy	European joint undertaking for ITER and the Development of Fusion Energy: integral part of the JT-60SA Project EU Home Team ensuring the coordination of implementation of the PA and its interfaces with other PAs in BA activities
FMEA	Failure Modes and Effects Analysis	A systematic techniques for failure analysis and the analysis of complex system's reliability
FPGA	Field Programmable Gate Array	Integrated circuit designed to be configured by the customer or designer after manufacturing
FPPC FPPC(u,l) FPPC(1,2)	Fast Plasma Position Control	Coils used to control the plasma position (classified as upper/lower or 1/2)
GPS	Global Protection System	System for handling the protection signals received from the equipment and distributing the protection commands
GS	Grounding Switch	Switches for SNU safety grounding
HMI	Human Machine Interface	Hardware/software for friendly high-level management
IAs	Implementing Agencies	F4E and JAEA
IDC	Identification Code	Code used for identification and traceability of JT-60SA components

Acronym	Term	Definition
IP code	International Protection code	International Protection rating code as defined in Standard IEC 60529
IPS	Internal Protection System	System to coordinate protective actions among all JT-60SA PS components and among them and the remaining parts of the JT-60SA system
IS	Industrial Supplier	The company selected by ENEA to provide the supplies, services or works described in these Technical Specifications, according to a Procurement Contract
ISCP	IS Control Plan	A relevant part of the ISQP
ISQP	IS Quality Plan	The Quality Plan issued by the IS according to the guidelines provided by ENEA in the present document
ISQR	IS Quality Representative	Quality Representative of the IS for the Procurement Contract
ISTRO	IS Technical Responsible Officer	Technical Responsible Officer of the IS in charge for the Procurement Contract
ITER	International Thermonuclear Experimental Reactor (ITER)	International research and engineering project which is currently building the world's largest and most advanced experimental tokamak nuclear fusion reactor
JAEA	JAEA	Japan Atomic Energy Agency
JT-60SA	JT-60SA	JT-60 Super Advanced tokamak, the construction and exploitation of which shall be conducted under the Satellite Tokamak Programme and the Japanese national programme
LCC	Local Control Cubicle	Local Control Cubicle
LCM	Local Control Mode	Local Control Mode of the operations
LSOHFR	Low Smoke, Zero Halogen, Fire Retardant	Type of insulation for cables and optical fibers (see also Standards IEC 60332-1, 60332-2 and 60332-3)
LV	Low Voltage	–
MQS	Management and Quality Specifications for the ENEA SCMPS IS	[ANX3]
PF, PFC	Poloidal Field (Coil)	In a tokamak, the poloidal field travels in circles orthogonal to the toroidal field
PID	Plant Integration Document	Document defining the technical basis of the JT-60SA Project [ANX1]
PoE	Port of Entry	Port of Entry in Japan (see [ANX2])
PA	Procurement Arrangement	Framework between F4E and JAEA for the main governing, financial and collaborative requirements for the supply of a procurement package
PM	Progress Meeting	Meeting between ENEA and IS to discuss the Contract status
PS	Power Supply	–
PS SC	Power Supply Supervising Computer	Computer provided by JAEA that communicates with SCSDAS, GPS and SIS and includes an IPS
QPC	Quench Protection Circuit	System to protect superconducting coils
RCM	Remote Control Mode	Remote Control Mode of the operations
RM	Reflective Memory	Real-time Local Area Network in which each computer always has an up-to-date local copy of the shared memory set
RMS, rms	Root Mean Square	Standard parameter of an alternating electrical quantity
Rnl	Non-linear resistance	Crowbar non-linear resistance
RWM	Resistive Wall Mode	Issue related to plasma stabilization
RTI	Raggruppamento Temporaneo di Imprese	-

Acronym	Term	Definition
SCB	Static Circuit Breaker	Switch system based on static devices that supports the BPS to satisfy the SNU time specifications
SCMPS	Superconducting Magnet Power Supply	Power systems, electrical and electronic devices to feed the coils of JT-60SA
SCSDAS	Supervisory Control System and Data Acquisition System	JT-60SA system
SIS	Safety Interlock System	JT-60SA system
Site, Naka Site	–	The location where the system object of these technical specifications will be installed: Naka, Japan
SNU	Switching Network Unit	System supporting a PS to abruptly increase its voltage
SS	Fast SNU Switch	Functional component of a SNU, that can be implemented by several physical devices, able to divert the coil current
STP	Satellite Tokamak Programme	One of the three projects in the BA activities with the purpose to develop JT-60SA
TF, TFC	Toroidal Field (Coil)	In a tokamak, the toroidal field travels around the torus in circles
–	Tokamak	Device using a magnetic field to confine a plasma in the shape of a torus
TS	Technical Specifications	The present document
UID	Unique Identifier	Code identifying a DMS document with current status, version, and so on
UPS	Uninterruptible Power Supply	APS provided by JAEA
VC-DI	Voluntary Contributor Designated Institution	Institution appointed by the Government of the countries (Voluntary Contributors) that give voluntary contributions to Euratom for the implementation of the BA activities
XFMR	Transformer	–