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Study, test of components and commissioning of the TJ-II radial field power supply

Master Thesis
Presented by

Kamal Mohamed Abdelaziz Ahmed

kamaltokamak@yahoo.com
CIEMAT, Madrid

Erasmus Mundus Master in Nuclear Fusion Science and Engineering Physics

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Kamal Mohamed Abdelaziz Ahmed

kamaltokamak@yahoo.com
CIEMAT, Madrid

Thesis Promoters

Carlos Hidalgo Vera

CIEMAT
Madrid, Spain

Gérard Bonhomme

Université Henri Poincaré
Nancy, France

Thesis supervisor

Javier Alonso

CIEMAT
Madrid, Spain

Erasmus Mundus Master in Nuclear Fusion Science and Engineering Physics

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List of abbreviations

Symbol	Description
DSP	Digital signal processing
CB	Circuit breaker
PLC	Programmable logic controller
DC	Direct current
AC	Alternating current
A/D converter	Analogue to digital converter
R coil	Radial field coil
TF coil	Toroidal field coil
VF coil	Vertical field coil
HXn coil	Helical coil number
OH coil	Ohmic coil
CC coil	Circular coil
LED	Light emitting diode
UPS	Un-interrupting power supply
Δ	Delta connection
Y	Star- connection
NBI	Neutral beam injection
ECRH	Electron cyclotron resonance heating
GDC	Glow discharge cleaning
HVPS	High voltage power supply
ZCT	Zero flux current transformer

Introduction

Experimental fusion devices confine the plasma with the help of magnetic field. Concretely, these fields have to reach levels of Tesla units, maintained with precisions of 0.1%, in volumes of tens or even hundreds m^3 (as it is the case of ITER project). The way to obtain this field is applying DC currents of tens of kA (with DC voltages of hundreds of volts) to the magnets of the device. These currents are typically obtained rectifying AC currents with high power converters with high accuracy (normally with much better accuracy than in general industrial applications). In addition to the confining of the plasma, it needs to be heated. The heating is accomplished in several ways: by ohmic currents induced in the plasma, by the injection of electromagnetic waves, or by injection of neutral particles. The last two systems of heating require electrical DC power supplies, typically with voltages of tens of kV and currents of units or tens of A.

Therefore, a medium or large-experimental fusion device can consume tens or hundreds of MW and requires different converters: some of them with high currents (for the magnets) and others with high voltages (for the plasma heating systems). Up to now, the fusion experiments operate in pulse mode. The principle of operation of a pulse power supply is to store slowly energy from the power grid with low power and then to deliver the stored energy to the device in a short time and with a high power.

First, and because the first fusion devices had a low power consumption and low confinement time, the power supplies simply consisted of a battery of capacitors. Later, the electrical consumption of the devices was increasing and so the power supplies consisted of rectifiers connected to the grid. Once consumption of the device reached tens of MW (pulsed), the power supplies had to be fed from electric generators instead of from the grid.

Most experimental fusion devices are today fed from on one or more generators. The basic feature of the operation of these electrical generators, is that the generator delivers the peak power during the experiment by transforming the kinetic energy stored in its rotor (by rotating at a certain speed), into electrical energy. This provokes a sharp reduction of the generator speed that could reach the 20% of the speed or even higher. After the experiment, the generator takes time to recover the speed, and be ready for the next experiment. Once the time of the experiment is extended, the use of superconducting coils is necessary.

The power supplies for devices with superconducting coils are not fed from generators, these power supplies are generally fed from electrical power networks with high voltage levels (110 kV or more) and high short circuit power.

In fusion, the harmonics produced by the thyristor rectifiers harm tremendously for achieving the required magnetic field for a good plasma confinement. This has led to rectify in 12 phases instead of 6 phases, in this manner each converter is composed by two 6-phase rectifiers working in series or in parallel with an electrical shift of 30 degrees. This shift can be obtained by the connexion group of the rectifier transformers (for example with delta star connexions). Another way to reduce the harmonics on the DC current is increasing the frequency of the AC current, so there are generators specifically designed that works at 100 Hz instead of 50 Hz.

The thesis is organized as follow: the first chapter gives a brief overview about the fusion energy and the confinement concepts; the second chapters gives a general overview about the TJ-II stellarator; the third chapter is about the power supply of TJ-II; the fourth chapter is devoted for the entire components of the rectifier set; the fifth chapter contains the results of the tests and the measurements. The last chapter summarizes the results and enumerates the major conclusions of the thesis.

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Abstract

The TJ-II is a fusion experiment located in CIEMAT (Madrid). It is a medium size stellarator with the purpose to explore a wide range of magnetic configurations with different rotational transform, shear and magnetic well. The plasma has a helical shape, 1.5 m major radius and ~0.24 m swing radius. All the components are arranged around these basic lines.

The magnetic structure of the stellarators depends only of the fields produced by a more or less complicated set of coils, without the influence of the possible net electrical toroidal currents in the plasma. Actually this toroidal current must be cancelled as much as possible in this kind of devices.

The basic magnetic structure in the TJ-II device if produce by four coil systems: the Toroidal Field Coils, the Circular Coil, the Helical Coils and the Vertical Field Coils. In addition there are two additional coil systems that normally are not in operation: the OH Field coils, designed to cancel toroidal net currents in the plasma, and the Radial Field Coils, designed to compensate any misalignment of the fore mentioned four basic coil systems during the assembly of the experiment.

The TJ-II operates in pulse mode, at a rate of ~3 seconds pulse every 5:8 minutes. All the coils operate with high DC current and with flat tops between 200 ms and 500 ms (plasma time). Each coil system has its own power rectifier supplied from a pulsed high inertia flywheel generator which accelerates during 5 minutes and release the accumulated energy in the rotary masses during the 3 seconds. In this way the rectifiers have to be operated and controlled at variable frequency, typically between 80:100 Hz.

The Radial Field Coil power rectifier was not operated during years because it has not been necessary to introduce any correction in the magnetic structure of the TJ-II, either produce by coil construction mistakes or assembly misalignments. Recently it was put on the table the possibility to use this field to move the vertical position of the plasma and to study the influence on the magnetic field structure.

The objective of the present work is to study the characteristics of all the power and control circuits of the rectifier, some of them dismantled to be used for other systems, to assembly new ones, to commission first in a separate mode the different parts, to operate the whole system with a dummy load to avoid any risk in the TJ-II coils, and finally with all the previous steps successfully completed, to test the rectifier in the Radial Field Coils. Within this task all the useful information in the voltages and currents of the circuits will be measured and presented.

Keywords: TJ-II, R-coil, Dummy load, Power supply, converter system, 12-pulse thyristor configuration, ZCT and harmonics.

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Chapter 1

Overview of fusion energy

1.1. Fusion energy

The world power demand will rise to tens of terawatts during the next century. Most of rise will be in developing countries, so efforts by industrialized countries to conserve energy will not prevent the power demand increase [1].

Energy sources having the potential to meet such energy needs are: fossil fuels, renewables, nuclear fission and fusion (in the longer term). Globally, fossil fuel resources are finite and their use is now confirmed as a serious threat to the global environment. Although the potential of renewables is large, their capability to provide base-load energy is questionable. A substantial fraction of our energy needs could be provided by nuclear fission, which has to solve public acceptability problems. Sustainable, CO_2-free energy sources are necessary in the long term [2].

Thermo nuclear fusion remains a long-term solution to the energy requirement. Fusion is generally conceded to be one (if not the) energy source that will provide mankind with long-term supply of plentiful and inexpensive energy. This prophecy is based on three key points. Firstly the basic fusion fuel (deuterium and tritium) are available throughout the world in almost inexhaustible quantities. Secondly, fusion reactor will be inherently safe from possible nuclear excursions and will present fewer radioactivity problems than fission rectors. Finally, very efficient energy conversion should ultimately be possible [3].

The aim of fusion research is to utilize the energy source of the sun and stars here on earth: A fusion power plant is to derive energy from fusion of atomic nuclei. Under terrestrial conditions this can most rapidly be achieved with the two hydrogen isotopes, deuterium (D) and (T). These two component fuse to form helium, thus releasing neutrons and large quantities of energy: One gram of D-T fuel could generate 100,000 kilowatt-hours of electricity: about 8 tones of coal are needed to supply the same energy. A cubic meter of water contains 34 grams of deuterium the energy equivalent of 300000 litters of oil. The oceans, the seas and lakes could supply enough deuterium for a 1000 reactors over a millions of years. With special conditions fusion needs an ignition temperature of 100 million degrees [4].

Fusion power stations will be particularly suited for base load energy generation to serve the needs of densely populated areas and industrial zones. They can also produce hydrogen for a “hydrogen economy”. The energy generated by the fusion reactions will be used in the same way as today, e.g. for the generation of electricity, as heat for industrial use, or possibly for the production of hydrogen. The fuel consumption of a fusion power station will be extremely low. A 1 GW (electric) fusion plant will need about 100 kg deuterium and 3 tons of natural lithium to operate for a whole year, generating about 7 billion kWh. A coal fired power plant without carbon sequestration requires about 1.5 million tons of fuel to generate the same energy!

Fusion reactors do not produce greenhouse gases and other pollutants which can harm the environment and/or cause climate change.

A simple measure of the performance in fusion machines is the Q factor, the ratio of the fusion power produced divided by the heating power applied to the plasma. A fusion plasma reaches the condition of self-sustained "burn" ($Q = \infty$) when the energy being lost from the plasma is balanced by plasma self heating due to fusion reactions. When this condition is reached, external heating is no longer required to maintain the high temperature conditions for fusion.

JET has generated 16 MW of fusion power at $Q = 0.65$. The next machine, ITER, aims at $Q = 10$, while future fusion reactors may have Q values up to 40 or 50 [5].

1.2. Confinement methods in fusion

There are two types of fusion confinement namely magnetic confinement and inertial confinement. Magnetic Confinement makes use of magnetic fields to ensure thermal insulation perpendicular to the magnetic field. Losses are reduced by closing the magnetic configuration on itself (doughnut-shaped ring). Magnetic Confinement Fusion uses a very low-density fuel (less than ambient air density), and confines the plasma energy for the order of seconds. It could allow steady state operation.

Inertial Confinement uses ultra high power lasers or ion beams to heat and compress a minuscule fuel pellet to about 1,000 times solid density, until ignition occurs in its core, the fuel explodes and spreads outwards releasing energy.

In the magnetic confinement fusion, a magnetic field is created in a "vacuum vessel". In an idealized situation electrically charged ions and electrons which make up the plasma cannot cross the magnetic field lines. They can however move freely along these field lines just like in a cage.

By bending the field lines around to form a closed loop, the plasma particles are, in principle, confined. Particles and their energy are kept well isolated from the wall of the vessel, thus maintaining the high temperature. However, in a real toroidal magnetic system there are losses of energy through various processes, such as radiation, and by particle collisions which cause particles to escape from the plasma across the magnetic field lines as time goes by.

The magnetic fields are generated by large electrical currents flowing in coils located outside the reactor vessel. Frequently, currents generated in the plasma also contribute to produce the magnetic cage.

The cost of fusion power depends on the efficiency of the confinement.

The efficiency measures are: (1) the field strength on the coils needed to confine a given plasma and (2) the ratio of the power output to the power required to sustain the current in the plasma and coils, or more generally, the re-circulating power fraction.

The magnetic field at the coils that is needed to confine a given plasma depends on two numbers: the plasma beta (β), which is the ratio of the plasma pressure to the magnetic-field pressure, and the second is the ratio of the magnetic-field strength on the coils to that in the plasma. The plasma pressure, or β, can be limited by equilibrium, stability, or transport issues. The power required to maintain the net current of a tokamak places significant constraints on the design [6].

1.3. Concepts of magnetic confinement devices

The two most prominent magnetic configurations for confining plasmas are tokamaks and stellarators. Both concepts rely on two magnetic field components, a toroidal component and a poloidal component, to produce a rotational transform resulting in helical field lines and closed magnetic surfaces able to confine the plasma.

In Tokamak, the plasma acts as the secondary winding of a transformer (the primary winding is an external coil) and a change of current in the primary winding induces a current in the plasma. As well as generating a magnetic field which plays a role in confining the plasma, this current also provides some heating, because of the plasma's electrical resistance. Since a transformer cannot generate a current continuously in the same direction, the plasma has limited duration and steady state must be sustained by other means.

Magnetic confinement in the stellarator is based on a strong magnetic field produced by external coils. The confinement scheme in the stellarator consists of modifying the magnetic field so that a single line of force, followed indefinitely, generates not a single circle but rather an entire toroidal surface, called "magnetic surface". The tube enclosing the plasma is ideally one of these surfaces, with an entire family of nested magnetic surfaces [7].

In addition to the tokamak and stellarator, many other magnetic configurations are being actively pursued in the world fusion program. The most prominent are the reversed-field pinch, the spheromak, and the magnetic dipole.

1.4. Tokamak concept

A tokamak is a device able to produce and confine a large volume of high temperature plasma a mixture of electrons and ions in a toroidal shape by means of strong magnetic fields. The original design principle was developed at the Kurchatov Institute in Moscow in the 1960s and due to its ability to maintain the temperature in the plasma the tokamak has become the most advanced magnetically confined fusion concept in the world.

Because fusion plasmas are extremely hot above 100 million degrees, it is necessary to keep the plasma particles away from the walls of the confinement device as much as possible. This is achieved with a combination of magnetic fields, generated through external coils, and by the current that flows in the plasma.

This “magnetic cage” creates helical field lines inside the machine around which the charged particles of the plasma gyrate and are kept confined.

The plasma current is normally induced by a transformer coil. Thus in its basic form, a tokamak does not work continuously, but in pulses. In order to achieve steady state operation in a future power plant based on the tokamak principle, at least part of the current has to be driven continuously by means of high-frequency waves or the injection of fast particles. Fortunately, a thermo-magnetic effect - the so-called "bootstrap" current – can then provide the remaining part of the current [2].

1.5. Stellarator concept

The stellarator concept was proposed as early as 1951 by Lyman Spitzer of Princeton University. Its name suggests a ‘star machine’, producing energy from fusion. This star machine uses strong magnetic fields to confine the plasma in a torus-shaped vessel, so in this respect, it is similar to a tokamak.

The difference is that stellarators rely entirely on magnetic fields produced by external coils to produce their magnetic confinement, eliminating the need for a toroidal plasma current but requiring a more complex shape for the coils than in tokamaks. The concept is then intrinsically able to maintain the confinement configuration without the use of the current drive systems which are needed in tokamaks. Disruptions, instabilities and other plasma events associated with the free energy of a large (several million A) toroidal current either do not occur or are strongly reduced. Stellarators offer an intrinsic potential for steady-state, continuous operation [8].

There are a plenty of ideas of how to externally produce a helical field. They can be divided into two groups. In the first group, the magnetic field is generated by an assembly of field coils of simple geometric forms, e.g. planar, helical. These devices require at least one coil to encircle the torus toroidally. The naming of these helical devices is given by the number of helical coils and the direction of the current flowing in them. The second group is the devices where the magnetic field is generated by modular field coils of complex-geometric shape that encircle the torus only poloidally. Optimizing the properties of the magnetic field coils were no longer required to be of simple-geometric shape [9].

A classical stellarator consists of a set of planar field coils that generate a toroidal magnetic field and a set of l dipole coils that are wound around the torus circumference n times.

W7-A (Germany) was such a l=2, n=5 classical stellarator. The currents in neighboring coils flow in opposite directions. The last closed flux surface clearly shows the three-dimensional structure of the plasma. The plasma cross section is approximately elliptical and rotates with increasing toroidal angle.

Helical magnetic field lines and nested flux surfaces can also be obtained if the currents in the helical coils all flow into the same direction; then the toroidal field component does not cancel and it is even possible to dispose of the toroidal field coils all together (lest one wants to retain them for some additional experimental freedom). Such a device is called a torsatron (heliotron in Japanese literature). In such a situation also the average vertical magnetic field does not vanish and it is necessary to add an additional vertical field (generated by horizontal coils) in order to form a magnetic axis. The advanced toroidal facility (ATF, U.S.A.) was a l=2, n=6 torsatron.

In a heliac, finally, the centers of the toroidal field coils are no longer in one plane but follow a helical line. TJ-II (Spain, operative since 1997) is a Heliac device. In TJ-II, a horizontal coil for an additional vertical field has been added to increase the flexibility of the magnetic field configuration.

In recent years the focus of stellarator research has become dominated by the demands of a fusion reactor. These studies include the investigation of: (1) parametric dependence of the plasma confinement on global quantities with the goal of extrapolating to the necessary size of a stellarator fusion reactor, (2) high beta discharges and the search for instabilities that might limit the maximum achievable plasma beta, (3) in-vessel components suitable to withstand high heat load and simultaneously causing little increase of impurity concentration in the plasma, (4) long pulse discharges to verify the steady-state viability, (5) non-inductive current drive to balance the internally generated plasma currents.

Stellarators are inherently capable of steady-state operation since plasma confinement does not require constantly driven toroidal plasma current. LHD (Japan) and W7-X (Germany) for example are equipped with super-conducting coils. It also requires plasma heating methods capable of steady-state operation. Appropriate sources for neutral beam injection and electromagnetic wave generation are being developed at present. In ATF a one-hour discharge has been achieved at small power level with electron cyclotron heating and low values of magnetic field and plasma density. In LHD plasma discharges at higher power levels and magnetic fields have reached a duration of several minutes.

In Europe, two Stellarator projects have been built, TJ-II in Spain and W7-AS in Germany. TJII is the only stellarator currently in operation but a new larger stellarator, W7-X , is under construction in Germany [8].

Chapter 2

Overview of the TJ-II stellarator

2.1. Introduction

TJ-II is a medium size helical axis stellarator (see figure 2.1) located in CIEMAT, Madrid, whose main parameters are shown in table 2.1. The main goal of TJ-II device is progress in the development of a disruption free, high density, steady state reactor based on the stellarator concept.

The objective of the experimental programme of TJ-II is to investigate the physics of a device with a helical magnetic axis and wide flexibility in its magnetic configuration. The physics problems of magnetically confined plasmas studied are of much interest to the fusion community [10].

Parameter	Value	Parameter	Value
Average major radius	1.5 m	No. of periods	4
Average minor radius	0.22 m	Pulse length (plateau)	0.2 : 0.5 s
Max. toroidal magnetic field	$B_0 \leq 1.2$ T	Discharge repetition rate	One every 5 min.
Maximum beta	6%	No. of coil systems	7
Rotation transform	0.9 : 2.5	ECRH power	700 kW at 48 GHz
shear	1 : 10%	NBI power (present status)	2 MW
Plasma volume	1.4 m^3	Input power	130 MVA
Plasma temperature	600-850 KeV	Plasma density	1.6 x 10^{19} /m^3

Table 2.1: The main characteristics of TJ-II stellarator.

2.2. The main components of TJ-II

The main components of the Spanish Stellarator TJ-II are:

2.2.1 The support structure

The support structure supports the hard core, the vacuum vessel, the 32 toroidal field coils and the poloidal field coils individually. No direct connections between the main components have been done in order to facilitate design, stress analysis, inter-phase studies and fabrication sequence. It is made of stainless steel 304LN to assure very low magnetic permeability values

(<1.01) and has a total weight of 25 tons. It is composed of four circular columns, four rings, eight radial beams and sixteen rectangular columns. These components were casted and welded together in order to remain within the casting capabilities of the manufacturer. The four circular columns have four meters long and a diameter of 250 mm. These columns are bolted together to the basement of the TJ-II torus hall to avoid possible magnetic perturbations from ferrite structures and materials in the magnetic structure. At the top of the columns, there a rigid cantilever arms where the four lower radial arms of the support structure are resting. The four strong steel rings has U-shape and are distributed as inner lower, inner upper, outer lower and outer upper. These rings are linked by eight radial arms: four for connecting the upper rings and the other four for connecting the lower rings.

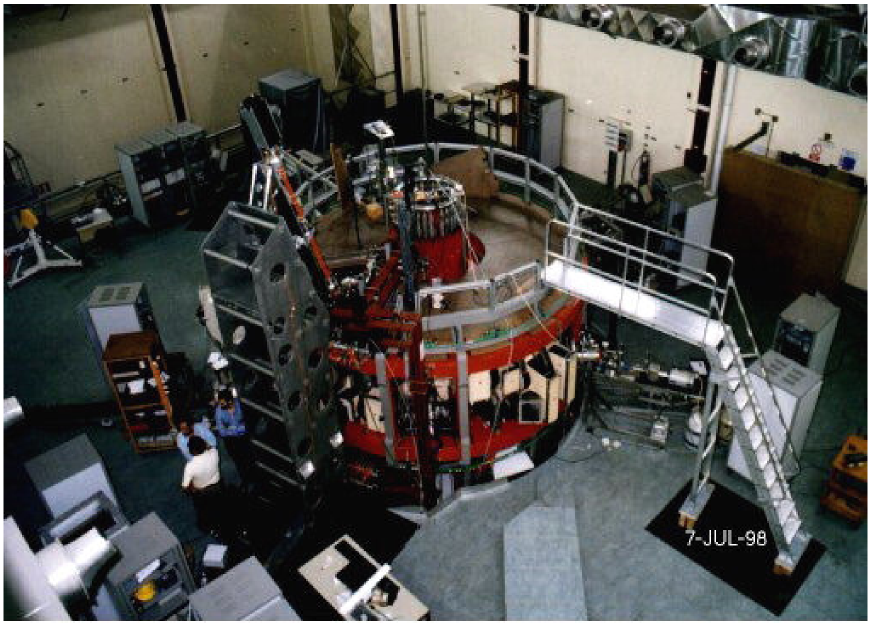

Figure 2.1: The helical TJ-II stellarator at CIEMAT, Madrid [11].

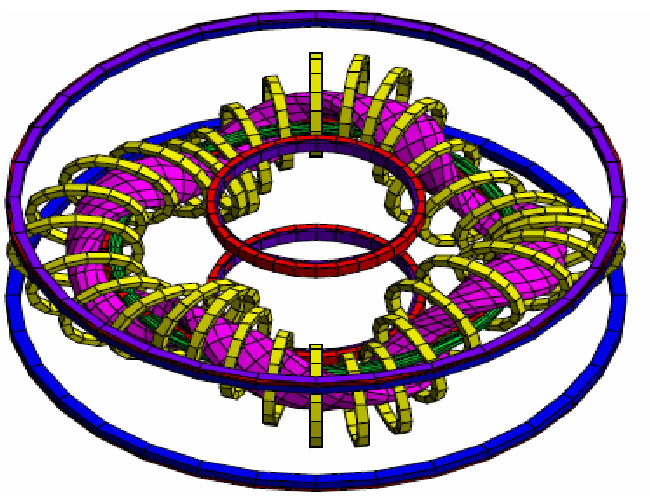

Figure 2.2: A schematic diagram of TJ-II magnetic field coils [11].

Finally, sixteen rectangular columns connect the upper and the lower rings (eight for the inside rings and eight for the outside rings). The columns and the rings, forming in this way a rigid cage to which all the parts of the device are to be attached [12].

2.2.2 Vacuum vessel

The vacuum vessel has a helical geometry. The centerline of it follows a helix around a horizontal base circumference 1.5 m radius with an average swing radius of 0.3 m.

It is made of 304LN (10mm thick) stainless steel with additional requirement of very low magnetic permeability values (<1.01). The vessel is an arrangement of 32 sectors and 32 rings alternatively distributed. Both sectors and rings have a groove (concave helical surface) in the area closer to the base circumference to allow the hard core to remain outside the vacuum vessel. The 32 rings correspond to the geometrical position of the toroidal field coils, which are assembled around the vacuum vessel. They have a circular section (except in the groove area).

The 32 sectors have a quasi-oval section enlarged respect to the section of the rings. The vacuum vessel has 96 ports with different sizes distributed in these sectors. The outmost eight sectors have 4 ports each, eight sectors have 2 ports each and sixteen have 3 ports each. Access for diagnostics and beam-lines has been provided by these ports. Vacuum vessel is hanged from the upper radial arms of the support structure.

The plasma facing material of the vacuum vessel of TJ-II is made of stainless steel AISI 304LN conditioned by carbon, boron and lithium. The interaction between the plasma and the vacuum vessel is mainly located in the region surrounding the central coil system, and therefore the set of stainless steels serve as a thermal shield.

This vacuum vessel can be heated by two ways. Firstly, 300 thermal resistive heaters are bounded to the vacuum vessel wall. Secondly, eddy current is produced by passing 400A controllable AC current through the toroidal field coils. The baking temperature of the vacuum vessel is 150°C [13].

2.2.3 Coil system

TJ-II comprises seven coil subsystems (see figure 2.2), which produce the magnetic fields required for the confinement of the plasma. All these coil systems which have the parameters as in table 2.2, are made of rectangular hollow copper profiles insulated with glass tapes and vacuum impregnated with epoxy resin and they have water-cooling channels.

The coil system consists of hard-core system, toroidal field system and poloidal field system. Hard core is composed of a circular coil (CC) and helical coil and it is supported from below at four points resting on the four lower arms of the support structure. The circular coil is enclosed in a stainless steel casing with some holes to locate the electrical and hydraulic connections.

It is a square cross section coil with mean radius of 1.5 m and 24 turns. The helical coil is a rectangular cross section coil wound around the CC with base radius of 1.5 m, swing radius of 7 cm and 24 turns. It is divided into two individually subcoils (HX1 and HX2) to be able to vary the distance between the mean lines of the current of the circular coil and helical one within certain limits. Both of these coils can be operated connecting them in series. The middle points of the subcoils are grounded to reduce the voltage to the ground at any point of the coil as much as possible. The mean lines of HX1 and HX2 run in parallel to each other and surround the CC coil four times. The independent supply of CC and HX coils allow to obtain a wide range of rotational transform [14].

parameters	TF	CC	HX1	HX2	VF	OH	R
Coil resistance (mΩ)	21.90	34.90	23.00	23.40	21.30	11.60	11.00
Coil inductance (mH)	05.18	04.57	01.32	01.33	07.00	02.70	00.97

Table 2.2: The parameters of TJ-II coils.

The toroidal field (TF) consists of 32 circular coils distributed with a four-fold symmetry and connected in series. Their centres lie on a toroidal helix around CC of major radius 1.5 m and swing radius 28.25 cm.

These coils provide a magnetic field up to 1.2 Tesla on the axis of TJ-II when supplied with their nominal current of 32.5 kA. The coils have eight turns each and are made of copper but the four most external TF coils have nine turns and are enlarged by 5 cm in order to allow the NB inlets and their centres are also displaced 5 cm in the radial direction . The coils are split into two halves for assembly reasons. The joints of the two halves are the most critical part of the coils. TF are supported in the four rings of the support structure. The coil structure has four arms bolted to these rings [15].

The poloidal field system consists of three different coil groups: vertical field coil (VF coil), ohmic field coil (OH coil) and radial field coil (R coil). VF group is composed of two coils, each with 16 turns. These coils provide the vertical field needed for the positioning of the plasma axis. OH group is composed of 4 coils; 2 outer coils with 1 turn and 2 inner coils with 20 turns that produce a low e.m.f along the magnetic axis of the plasma, to compensate the possible toroidal currents caused by plasma heating. R group is composed of 4 coils; 2 outer coils with5 turns and 2 inner coils with 7 turns, placed close to the OH coils provide a radial trimming field of 10 mT. The purpose of this coil is to compensate possible error in the construction, misalignments during the assembly and to generate radial field to compensate the radial force on the plasma. The poloidal field coils are embedded into the U-shape four rings, which are part of the support structure. Each coil system is supplied by two 6- pulse controlled thyristor converters connected in parallel. The total required peak power during the pulse is as high as 130 MVA and cannot be delivered directly from the utility grid; therefore, a pulse flywheel generator is used to feed the thyristor rectifiers.

2.3. The auxiliary system of TJ-II

2.3.1 Vacuum system

A vacuum system capable to produce base pressure in the range of 10^{-8} mbar is installed in TJ-II. Three different scenarios are foreseen for the vacuum system: pumping down from atmospheric pressure, plasma discharges and glow discharges. A low base pressure and short pump-down time are in the first mode, while the system keeps a relatively large gas flow of light gases (H_2, He) corresponding to total pressures of ≈ 10^{-3} and 10^{-2} mbar respectively in a continuous way in the two last cases.

The main components of the pumping system from the high vacuum to the fore vacuum side are: connection piece, isolation valve, turbo-pump and rotary pump. The measuring instrumentation includes a set of manometers and mass spectrometers. The pumping system has a set of four symmetrically spaced turbo-molecular pumps with nominal pumping speed of 1600 l/s each and a time constant of less than 1 s. They are coupled to the vacuum vessel through bottom ports having the maximum conductance (4760 l/s). This setup yields an effective pumping speed of 4000 l/s at the vessel to remove the gas produced in the process (water, methane, carbon monoxide ...etc) [17].

A set of total and partial pressure gauges are installed for vacuum characterization. Ionization gauges compatible with the magnetic field are used for the UHV side. Low-pressure capacitance manometers are used during the GDC and during the plasma shots due to their insensitivity to magnetic fields. Two mass spectrometers are installed; one of them for a residual gas analyzer (RGA) is installed directly in the TJ-II vacuum vessel with a heated, high conductance connection. The other is a quadruple mass spectrometer, differentially pumped that is connected to the TJ-II vacuum vessel through a low conductance hole and pipe setup. It is used for monitoring and optimizing GDC conditions and as plasma diagnostic between discharges.

The conditioning of the vacuum vessel before the initial experimental campaign is performed by helium glow discharge cleaning at room temperature. The glow discharge is carried out by applying a DC voltage of about 300 V to two L-shaped stainless steel anodes, spontaneously refrigerated and fixed into the vessel. The total discharge current is typically 1A per anode, equivalent to a current density of about 4-μA cm^{-2}. The discharge is started up by applying a DC voltage of 1000 V and with the help of a short injection of argon. When the glow is started, the argon injection is switched off and the discharge is sustained at helium pressures of 5* 10^{-3} mbar using a feedback-controlled gas injection system. At this pressure, the pumping speed of the vacuum system is about 2400 l/s. The gas injection system (GIS) consists of eight fast piezoelectric valves, symmetrically located around the vessel.

It is able to deliver gas fluxes above 100 mbar l/s, with a time response of a few milliseconds. Fluxes were inferred from the pressure rise into the chamber, as measured by a fast ionization gauge [18].

2.3.2 Power supply

The electrical power supply consists of a 15 kV, 100 Hz pulse generator of 132 MVA, 100 MJ, and seven 12-phase rectifiers of controlled thyristors for the coils and two non-controlled rectifiers for NBI.

The pulses of TJ-II can not be done directly against the main grid because of the high energy involved and the shot duration. To avoid the flickers in the grid a special power supply was installed. This power supply contains mainly of motor-generator, a set of power transformers, AC/DC converters, a dedicated control system and a protection system. It will be described in detail in chapter 3.

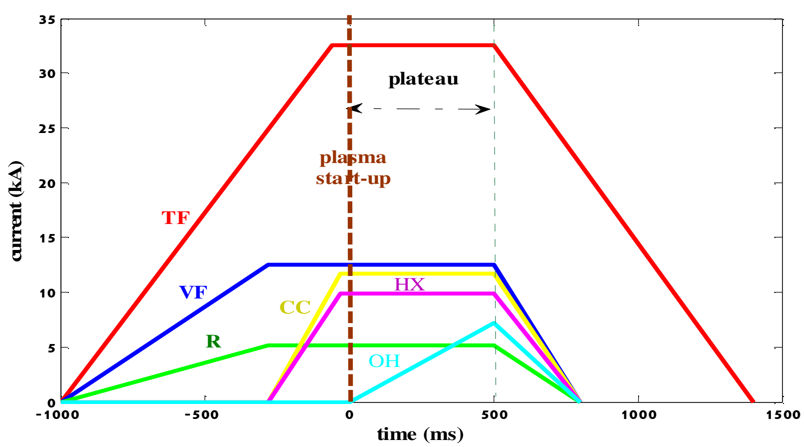

Figure 2.3: the scenario of the current discharge times of TJ-II coils.

The discharge currents scenario of TJ-II coils is shown in figure 2.3. The zero-point is the plasma start-up. TF coil begins to charge at 1sec before the start-up, and then its current becomes a flat-top at 60 msec before the plasma start-up. VF and R coils begin to charge with TF coil and their currents become flat-top at 250 msec before the plasma start-up. CC, HX1 and HX2 coils begin to charge when VF and R current becomes flat-top and their currents become flat-top at 30 msec before the plasma start-up. OH operates depending on the current that needs to be compensated. TF coil becomes fully discharged about 1s after the end of the plasma while the other coils are discharged about 300 msec after the end of the plasma. The plateau length varies from 0.2 to 0.5 s.

2.3.3 Heating system in TJ-II stellarator

Plasma heating methods are ECRH and NBI. The ECRH power supply can be fed from the grid or from the output of the generator but usually it is fed from the grid while NBI system in TJ-II is fed from the output of the generator because they need high power. There are foreseen two additional NBI systems in order to get a maximum power delivered to the plasma of 4 MW.

The ECRH system consists of two 350 kW gyrotrons (f = 53.2 GHz) with a pulse length up to 1s. The gyrotrons are coupled to the plasma by means of two quasi-optical transmission lines. One of the transmission lines is used for perpendicular injection of power to the plasma. The other is equipped with a mobile mirror located inside the vacuum chamber. The mirror can rotate in both poloidal and toroidal directions to allow selective power deposition, inducing current by electron cyclotron current drive.

The static transmission line has a power density of 1 Wcm^{-3} at resonance, and the corresponding power density for the mobile transmission line is 25 Wcm^{-3}. A power transmission efficiency of 0.9 has been achieved along the mirror lines, and the wave beam diameter is ≈ 10 cm and ≈ 2 cm at the plasma edge for the static and mobile transmission lines respectively. The electron kinetic energy in ECRH heating does not exceed more than a hundred keV. Higher temperature is nowadays obtained by coupling the ECRH with NBI.

In TJ-II, the NBI heating is achieved by using two injectors, with a capacity of 1 MW each. The injectors operate at 30-40 kV and current of 40-100 A. In the NBI heating, a beam of ions are produced and accelerated to high kinetic energy in the ion source and crosses a neutralizer, where they are partially neutralized by charge exchange. Residual ions are deflected away magnetically and dumped. The neutralized beam then passes through different beam apertures existing in the beam path before entering a 0.9 m length duct between the beam box and TJ-II. Beam simulation shows that only 60% of the neutralized beam reaches TJ-II plasma [19].

The lower power transmission is due to the high beam divergence, and the narrow beam pass through the duct and vacuum vessel port. One of the methods to improve the power transmission efficiency is decreasing the re-ionization losses by keeping the residual gas pressure sufficiently low.

2.3.4 Diagnostic system

Diagnostic systems are composed of sensors that are used to indicate the device status and to measure the different magnitudes of plasma:

- Electronic and ion temperature and density, Content of impurities, losses due to radiation, Energy contained in the plasma,
- Toroidal and poloidal rotation of plasma (Spectroscopy of plasma impurities.),

- Electrical and magnetic fluctuations and instabilities, Electric currents in the plasma.

TJ-II has different diagnostics:

- Rogowski coil, Mirnov coil, Diamagnetic coil to determine the magnetic parameters.
- Thomson Scattering to measure the electron temperature and density profiles.
- UV-Visible Spectroscopy, as a monitor of impurities in different spectral ranges. (Medium or low spectral resolution) by using an optical element (lens, mirror, set of them), a dispersive element (prism, diffraction system) and a detector (photomultiplier, photodiode ..) or sensitive plate (CCD camera) which measures the light.
- Reflectometry to measure density profiles and fluctuations, Interferometry, line integrated electron density, X-ray to determine the electronic temperature.
- Langmuir probe, which is used for de measuring the electronic density and temperature.
- The CX spectrometer measures the energy of neutral atoms that are emitted at in the plasma edge from the plasma (ion temperature diagnostics).
- Heavy Ion Beam Probe: HIBP, which can be used to determine fluctuations of electric potential and density, and Diagnostic NBI, rotation and ion temperature [11].

2.3.5 Monitoring and control system

The monitoring and control system has a total of 805 installed sensors.

The structure of the system is based on the standard VME (IEE803:2) with embedded processors running the real time operating system OS-9. For the realization of the graphical user interface, the software package G-Windows is used. The control system of TJ-II has different subsystems: fast control, vacuum vessel control, coil protection, grounding and timing subsystems.

Fast control subsystem is used for controlling and monitoring the physical processes on a millisecond time scale, which is the strongest demand on time response in the TJ-II control.

The fast control has the following main tasks: initiation of the slow and fast sequence in the timing System, real time calculation of delivered energy in the coils during the pulse, on-line generation of currents profiles, and signal interchange with the power supply system through an optical interface. Hardware links between the fast control and the power supply system guarantee a safe transfer of interlocks, alarms and emergency signals.

The real time protection functions related to maximum current and energy in the coils during the pulse were proved with several set points.

Three modes of operation (A, B, and C) have been defined, in order to provide pulse sequence flexibility. The operation modes depend of which system generate the profile currents references and timing signals. Table 2.3 summarized the modes of operation. Graphic screens are developed for the handling of the system. These screens include facilities for the system operation and pulse results such as: current ripple in each coil, maximum and minimum current during the flat top, delivered energy and graphical representation of the currents. A set of seven dedicated optical detectors are used to supervise the fuses status that connect the middle point of each coil to the ground.

Vacuum vessel control subsystem has two main tasks: Vessel protection during the shot and controlling of the baking process of the vacuum vessel up to 150°C. The following sensors have been installed in the vacuum vessel system: 20 displacement transducers, 256 solid-state relays, for the heating of the vessel.

The coils protection subsystem controls the water flow and the temperature of the cooling water in the hard core coil system and monitors pressures, temperatures, mechanical displacements and currents in all coils.

The Grounding subsystem must guarantee two objectives: First, protection of personnel and equipment from electrical faults in the machine enclosure and diagnostics area. Second objective is the minimization of electromagnetic interferences in diagnostic and control signals, by reducing ground-loop currents owing in signal cable shields.

The Grounding System is split up into eight single parts, which are connected at the single ground point situated near the TJ-II structure in torus hall. Control and diagnostic performance can be compromised if any single branch ground comes in contact with another one.

The master timing subsystem provides the clock, trigger signals and events used to synchronize the power supply, gas injection, ECRH, NBI, diagnostics equipment and the data acquisition system during the pulse sequence. The PSK (Phase Shift Keying) modulation technique is used to distribute simultaneously both timing and event information via optic fibre link. The system provides absolute timing references with a variable time resolution ranging from 500ns to 1ms, depending on the span time selected, but in all cases, with a precision of 500ns. The timing system is divided into two sections: firstly, the machine section (one VME crate) which includes the main clock generator (MCG) and 40 independent timing generators and secondly the diagnostics section with 120 independent timing generators housed in three VME crates. In both sections all I/O signals are linked via an optic fibre highway [11].

	Mode A	**Mode B**	**Mode C**
Timing signals	Power supply	Fast control	Fast control
Current profiles	Power supply	Power supply	Fast control

Table 2.3: The operation modes of control system of TJ-II.

Chapter 3

TJ-II power supply

3.1. Introduction

TJ-II requires a pulsed power supply system to feed its magnetic field coils and the plasma heating systems with a maximum total power of 132 MVA during 3 s each 5 min. This pulsed power can not be delivered by the main grid because of the high energy involved in short duration. To avoid the flickers in the grid a special power supply was installed. This power supply is mainly composed of a motor-generator subsystem, the seven power converters for the coil systems, monitoring and control system and the NBI power supply.

The motor- generator subsystem is mainly consisted of a synchronous generator, a motor pony, a cooling system and a protection system.

Each converter subsystem is mainly consisted of: a power transformer, a 12-pulse thyristor, and a no-load breaker [16].

The NBI power supply system consists mainly of two high voltage power supplies (HVPS) to feed the two neutral beam injectors. These injectors can provide to the TJ-II plasma an additional heating power of 2 MW with a maximum beam energy of 40 KeV.

3.2. Motor-Generator subsystem

The input from the grid is 15kV/50Hz. The motor generator system consists of (see figure 3.1):

3.2.1 Three-phase synchronous generator

The generator is an air-cooled salient pole synchronous generator with self-excitation. It has a maximum speed of 1500 rpm and it has four pairs of poles. The maximum excitation power is about 2 MVA. The generator is designed to deliver up to 132 MVA during 3 s and with a nominal output voltage of 15 kV at a maximum frequency of 100 Hz. It has a short circuit power of more than five times of its nominal power. It has an extractable energy of 158 MJ with a speed drop of 20%.

The generator is excited to its nominal voltage only during the experimental pulse for about 20 s every five minutes duty cycle. In the case of magnetic field mapping, where only small DC currents are required, the generator output voltage is reduced to 1.5 kV. The pole head is designed so that one side is tightening to the shaft to avoid the axial migration and the other side is designed in such a way that the thermal expansion is available to avoid higher oscillations.

During the pulse, the generator must provide a power much higher than the one it is receiving from the motor. The motor provides to the generator a maximum mechanical power of 1.5 MW while the generator must provide to TJ-II a power up to 132 MVA. Therefore, the generator transforms its kinetic energy into electrical energy and for this reason; a high sudden decrease of the speed is achieved.

The frequency varies from 100 Hz to 80 Hz with a speed variation from 1500 rpm and 1200 rpm. The generator output voltage should never exceed 16.5 kV during the pulse (which maximum duration is 40s); the maximum current of the generator is 5 kA. The generator has a saturated sub-transient short circuit power of 840 MVA at 100 Hz. The stored energy is 373 MJ at 1500 rpm and 158 MJ for a speed drop of 20%.

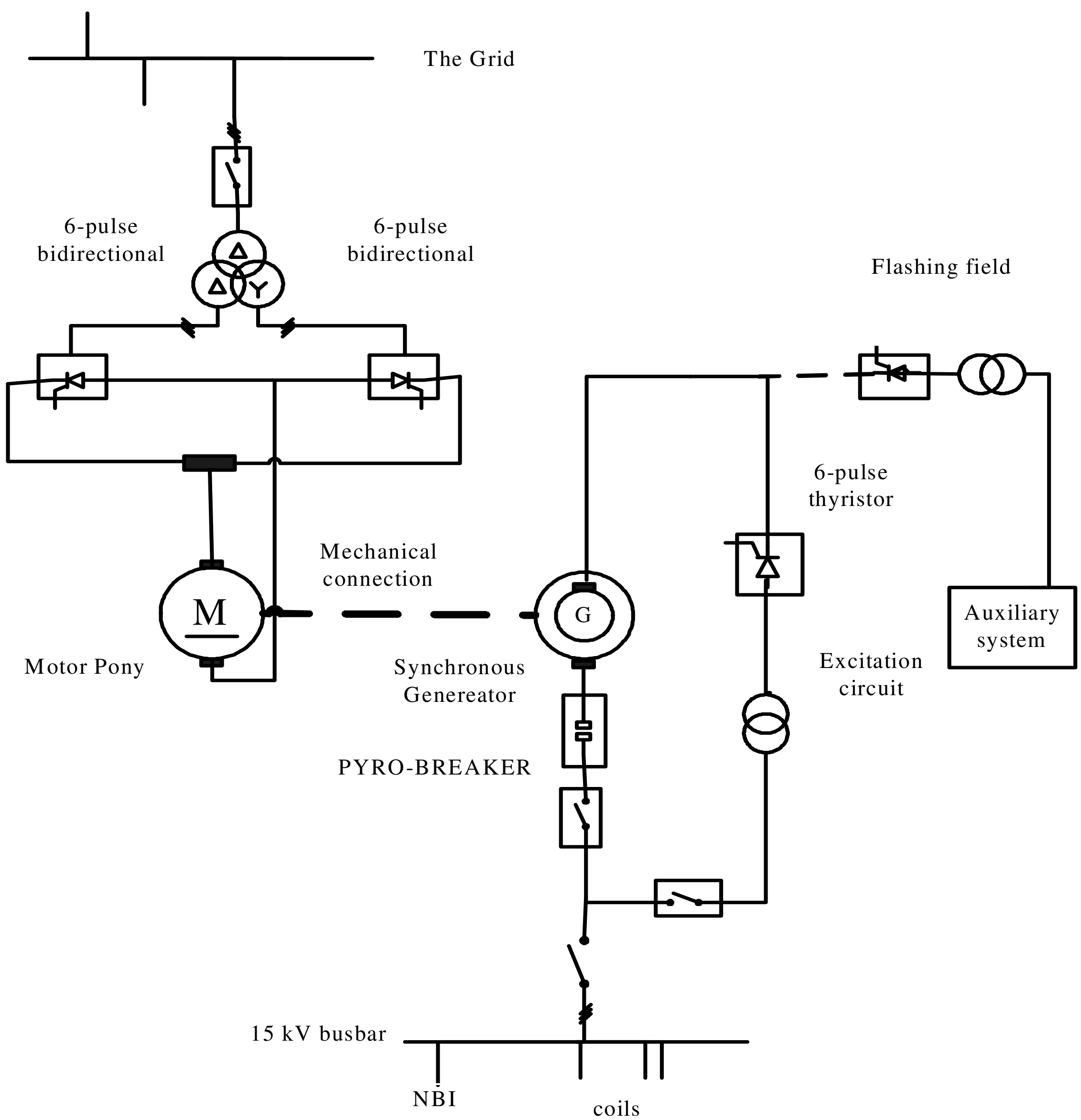

Figure 3.1: The schematic diagram of the motor-generator circuit.

3.2.2 Excitation system and field flashing

The generator is excited by a current converter that is supplied directly from the generator output. The current converter is consisted of a 6-pulse rectifier, a transformer 15000/550 V (with a power of 1 MVA), and a circuit breaker for 1250 A. There is also a flashing field connected to the low voltage grid through a 6-pulse low power rectifier and a transformer. This flashing field is connected to the generator only during the first moment of the generator start-up.

3.2.3 Generator protection system

The generator is equipped with a pyristor protection system installed at its output. It is able to open the circuit in case of a short-circuit before its asymmetric short circuit current peak is reached. The element that actually opens the circuit consists of two parts. One part is a very fast opening percussion operated by a bypass switch, and the another part is a limiting fuse (Pyro-breaker) connected in parallel across the percussion switch. It is designed to be triggered by an electrical discharge supplied by a controller that is isolated from the breaker by an isolated transformer. It has a motor, which contains an explosive charge. This charge can be exploded in the case of detecting threshold value (current and di/dt) by firing the detonator through the controller.

At the output of the generator, there are a twenty-one; 100 Hz medium voltage cells, which house the fast breakers. They organized as follows: 17 cells house SF6 circuit breakers: these breakers can interrupt the current due to a SF6 gas jet directly to the current arc. One houses an isolator, another measuring element, and finally there two cells for reserve feeders. Another six medium voltage cells interface the plant with the 15 kV, 50 Hz public network.

The generator is protected from over-voltages, over-currents, ground faults, over-temperature, over-speed, earth fault currents, excitation over current and over voltage, current unbalance, and phase error. In case of a fault, this protection system informs to the control system, to the excitation system and also to the motor converter to execute the break down of the motor-generator.

The protection system also sends the opening order to the output breaker of the generator and to the excitation breaker

There are also mechanical protections like: over-speed (mechanical and digital protection), winding temperature, oil pressure, oil temperature and vibration. There is an oil pump moved by the rotor shaft to provide lubrication oil for the rotor bearings at the normal operation. There are two spare systems for this purpose: one is a battery driven oil pump and the other is a gravitational oil system to provide the oil to the bearings by the gravitational force.

3.2.4 Pony motor

The motor pony is used to drive the generator and it is continuously connected to the public grid through its converter. Its main functions are: to start up the generator from zero to its maximum speed within 20 min, to speed up the generator between the pulses from 80 to 100% of the speed in less than 5 min and to stop from the maximum speed to zero.

The DC-pony motor has a maximum power of 1.5 MW and a maximum speed of 1500 rpm. The maximum parameters for the induced winding are: 700 V and 2263 A. The speed control is done by the control of the motor induced voltage. It is air cooled motor with an air/water heat exchanger. The motor is designed to give its energy to the grid during the generator shut-down.

This DC motor is connected to the generator shaft through a semi-elastic torque limiter. If the torque between the motor and generator exceeds a certain limit (overload clutch), the coupling will disconnect both machines and each one can rotate at different speed.

3.2.5 Motor converter

Its function is to feed the pony motor (rotor and stator windings) and to control the speed of the motor. The motor converter is designed to be compatible for reducing the voltage fluctuations on the grid, providing energy during generator operation in the case of long-pulses, maintaining the harmonics of the current as low as possible and having an easy speed control of the motor-generator set. The latter feature is important for reducing the energy consumption from the grid during the experimental operation.

It is a bidirectional thyristor current converter and it is connected directly to the grid through a 3-phase transformer with two secondary windings; Δ/Δ and Δ/Y connection which has a rating of 15000/695 V with a power of 2*1.1 MVA. It is composed of two 6-pulse bidirectional rectifiers connected in parallel through an iron-core interface reactor to minimize the current harmonics. This configuration allows delivering the energy stored in the motor generator back to the electrical grid during the braking phase. It feeds the motor in order to provide a regular speed and smooth load control. The motor converter controls the motor speed during the run-up, between the pulses and also during the shut-down of the generator [21].

3.2.6 Lubrication and cooling system

The lubrication system is equipped with three types of oil pumps. The high pressure electrical pump has to lift up the generator shaft before the beginning of the acceleration. The DC electrical pump must supply the adequate oil flow to the generator sleeve bearings while the velocity is below 500 rpm. The mechanical pump driven by the generator shaft has enough capacity to lubricate the bearings when the rotation speed is above 500 rpm.

The cooling system has only one electrical pump with a capacity of 2360 l/min which is sufficient to provide the necessary water flow for the motor pony air cooled heat exchanger, for the generator air cooled heat exchangers and for the oil-water heat exchanger of the lubrication system [22].

3.3. Converter subsystem

The output of the generator is connected to a busbar that feeds seven converters and the power supply for NBI heating system.

The function of these seven converters is to transform the 3-phase 15 kV output voltage of the generator to a continuous signal with high DC current and low DC voltage that feed the coil systems of TJ-II. Each converter set consists of a current breaker, two power transformers, two sets of 6-pulse thyristors connected in parallel through an iron-core interface reactor coil, and a no-load breaker. Also at the output of the generator, a synchronous transformer is placed to reply the input voltage to the control part [22].

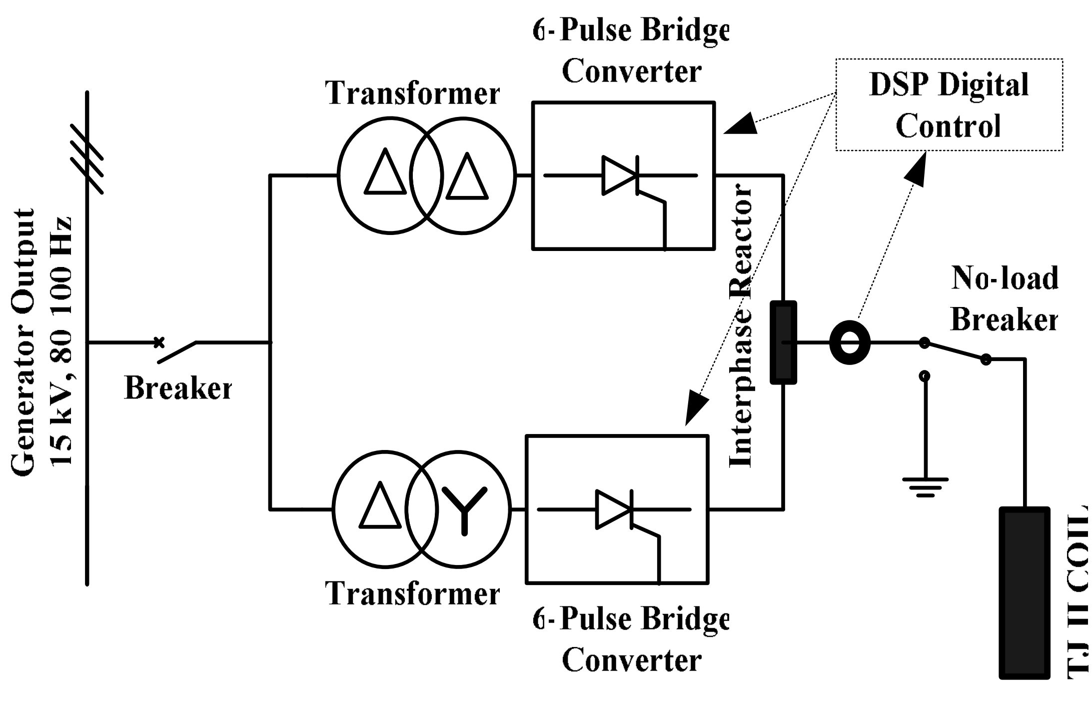

Figure 3.2: schematic diagram of the power converter for one coil.

3.3.1 Breaker:

The output of the generator feeds the rectifier transformers through 15 kV switchgears. These breakers can disconnect the converter transformers from the 15 kV bus bars with a response time shorter than 70 ms.

Each converter has its own circuit breaker, this breaker opens the circuit when the current exceeds rating limit.

This rating is different from one converter to another i.e., the rating of the TF branch is 1250 A and the others is 630 A.

3.3.2 The rectifier transformer:

In each converter, there are two 3-phase transformers (Δ/Δ and Δ/Y connection) which are housed in one oil tank. This connection provides 30° phase shift between the secondary voltages. The transformers are used to step-down the generator-output voltage to a certain value for each coil. The winding and the connections are made of copper. Six current transformers are located one in each phase of the primary winding of both transformers for the backup measuring and protection purposes. The primary nominal voltage is 15 kV. In addition, the frequency varies from 100 Hz at the beginning of the pulse to 80 Hz at the end of the pulse. The converter transformer is always connected to the reduced output voltage of the generator (1.5 kV) to avoid the inrush currents. It is switched off from the output of the generator in case of fault and it is designed to withstand the short circuit current.

In addition, the isolation test at the factory was done at 45 kV (primary to ground or primary to secondary). The 6-phase impedances including the internal connection are balanced so they are within 3% of the mean value. It uses mineral oil for the insulation and it has a thermometer to measure the temperature. The characteristics of the power transformers of the different coils are shown in table 3.1.

Trans. type	Transformer rating (V)	Trans. Power rating (MVA)	Rating current on secondary (kA)	CB rating	Load losses (kW)	No load losses (kW)
TF	15000/956	2*21.5	2*13.2	1250	876	15.2
CC	15000/790	2*7.05	2*5.10	630	220	6.8
HX1	15000/480	2*3.75	2*4.50	630	133	4.7
HX2	15000/480	2*3.75	2*4.50	630	133	4.7
VF	15000/440	2*4.15	2*5.40	630	153	4.8
OH	15000/210	2*1.00	2*2.70	630	58	1.5
R	15000/138	2*0.45	2*1.90	630	35	0.9

Table 3.1: The converter transformer characteristics.

3.3.3 Thyristor converters

The thyristor converters are two-quadrant 12-pulse converter to provide the required DC current for the TJ-II magnetic field coils, consisting of two 6-pulse rectifier connected in parallel through an iron core interphase reactor. Except the TF converter which has a total of 6 units of 6-pulse rectifiers: three units connected in parallel per branch. Then the two branches are also connected in parallel through an iron core interphase reactor. This topology is the most appropriate to deliver high currents at relatively low voltage levels with low harmonics levels.
Special requirements on these converters are the high precision of the currents, the low current ripple allowed and the variable frequency of the AC input voltage. The maximum DC output currents for the coils are between 5 kA and 35 kA. The output voltages have a range from 150 to 1000 V.

Rectifiers, interphase reactor, thyristor-firing pulse amplifiers and DC current transformer are mounted in one rigid steel frame. The thyristors are water-cooled. The control electronics are mounted in a separate cabinet which has located 15 m away from the current converters.

The DC current is measured by a zero flux current transformer with an accuracy of better than 0.01 % and an output signal bandwidth from 0 to 20 kHz. The latter is necessary to measure the harmonics contained in the DC current.

The table 3.2 shows the main characteristics of the seven thyristors converters: nominal DC output currents and voltages, number of thyristors together with their rated voltages and currents.

Coil	Nominal current (kA)	Nominal voltage (kV)	No. of thyristors	Rating (Vmax/Irms)
TF	32.5	1.05	36	2400V/5700A
CC	11.7	0.90	12	2200V/5700A
HX1	10.9	0.50	12	1200V/5700A
HX2	10.9	0.50	12	1200V/5700A
VF	12.5	0.50	12	1200V/5700A
OH	07.2	0.20	12	1200V/2800A
R	05.2	0.15	12	1200V/2800A

Table 3.2: The current converters characteristics.

3.3.4 No-load breaker:

Each of the seven coil system is connected at its input to a three-position switch called no-load breaker. In the first position, it allows the coil system to connect to ground during the non-operation or during any TJ-II maintenance. In the second position, it allows the two coil terminals to be opened (normally for measurement purposes). In the third one, it connects the coil system to its converter. It can not open the circuit when a current is circulating in it. This no-load breaker is motor driven and controlled from a local control or remote control.

It has an operational voltage 3600 V and operational current of 4000 A for TF coil. For CC, HX1 and HX2 coils, it has an operational voltage 1000 V and operational current of 800 A. Finally, for OH and R coils it has an operational voltage 1000 V and operational current of 630 A and 400 A respectively.

3.3.5 Synchronous transformer

At the output of the generator, there is a synchronous transformer. It introduces to the rectifier control system a reply signal of the input voltage of the converter with lower amplitude. It has the same connection group like the power rectifier transformers.

This signal is used to synchronize the firing pulse of the thyristors. This signal can not be taken from the secondary side of the rectifier transformers, because it is highly affected by the thyristor commutation. Therefore, this signal is taken from the output bus bar of the generator through a 15 KV transformer Δ/ Δ and Δ/ Y connection and ratio 15 kV/110 V with power of 5 KVA. The whole converter system cannot be operated in case of a synchronous transformer failure.

The 110 V signal is provided to the seven rectifier control. In case of star-primary connection of the CC, HX1 and HX2, the synchronous transformer does not connect directly to the general control system but it is connected to an intermediate transformer to arrange the output voltage (signal and phase).

3.4. Monitoring and Control system

All-important data (power, voltages, currents, speeds, temperatures, etc.) which are continuously recorded in a real-time control system and all reading are available on the control room. Figure 3.3 shows the monitoring and control system for the TJ-II power supply.

The monitoring and control system comprises one central computer HP/E25 and two satellite computers HP RT-743. The central computer carries out the system management and data storage, provides data bases and has the server capabilities for the user interfaces. Its characteristics are: 32-bit RISC-PA architecture, 48 MB of RAM, 4 GB SCSI disk, and 2 GB digital tape. This computer is connected to the two satellites by Ethernet LAN 802.3 cable. One of the satellite computers with a RAM of 16 MB carries out the input/output control and data acquisition for the generator and the other for the converters. Three UNIX workstations HP-715 are used as operator interfaces for the local control. At these workstations, all the monitoring and control data required for the operation of the entire system are available. Start and stop procedures are only possible at these terminals. Another UNIX workstation of the same type is used for the remote control of the power supply system.

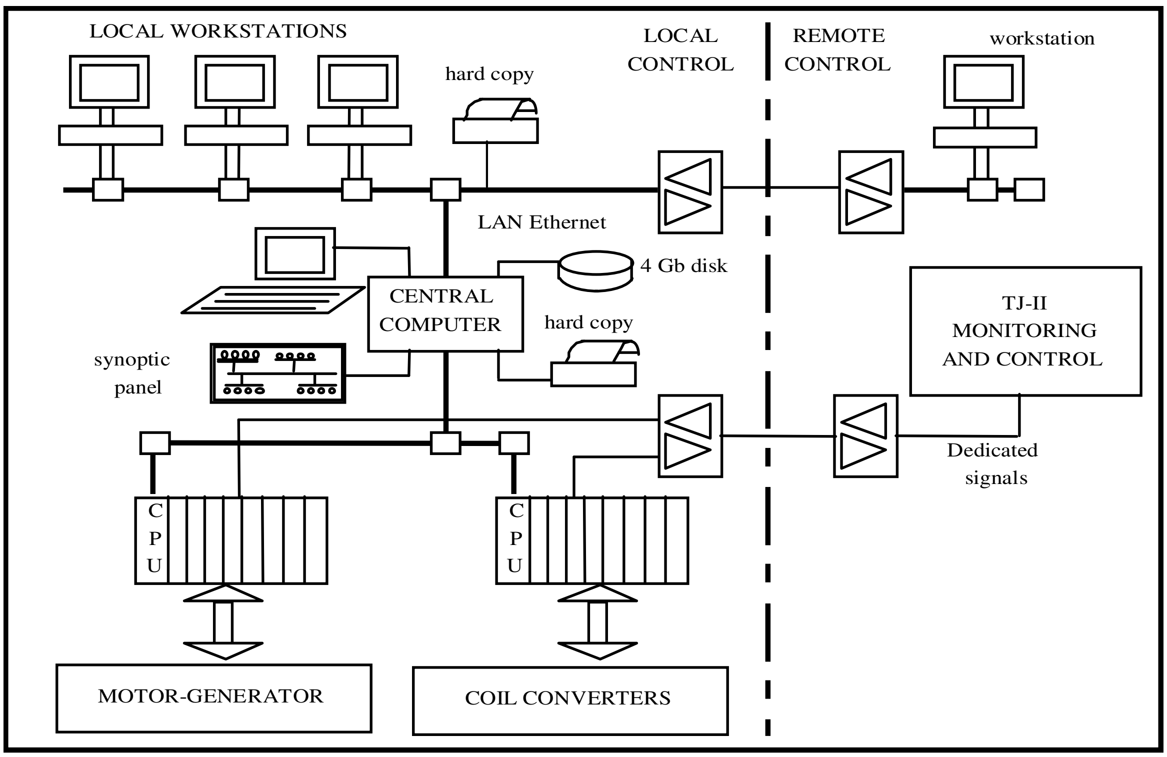

Figure 3.3: Monitoring and control system for the TJ-II power supply.

This workstation is located in the TJ-II general control room some hundred meters away from the power supply system and it is connected via an optical fibre cables. Monitoring and control of the power supply in normal experimental operation can be done at this terminal. It will be activated after the start-up of the power supply system and de-activated before shut-down of the system. A fiber-optic link to the general control of the experiment will allow the physicist in charge to vary the parameters of the power supply system independently.

The control system allows three modes of operation. In mode 1 the power supply works autonomously. This means that parameter setting will be done entirely within the power supply system. Only synchronization signals will be sent to the experimental device and the ready for pulse signal will be received from there. In mode 2 the DC currents are pre-programmed or the

reference values are produced within the power supply system but the timing will come from outside. In mode 3, reference values and timing signals are provided externally. The reference values will be transmitted as real time signals during the pulse.
Motor-generator and all auxiliary system: lubrication system, refrigeration system…etc interchanges signals with the control system. According to monitoring, the more interesting values - Idc current, Vdc voltage, etc. - are stored by the control system during the pulse.
The high frequency (1 kHz) and accuracy requirements for these signals do not allow to be acquired and processed straightly from the central computer. Therefore, all the pulses are stored at the satellite computer and then through optic fibre Ethernet load it at the HP/E25 central computer for processing [23].

3.5. The power supply to the NBI system

Two neutral beam injectors will be used to provide additional heating power of 2 MW and a maximum beam energy of 40 KeV to the plasma of TJ-II.
The two high voltage power supplies (HVPS) to feed the acceleration grids of the injectors, are of the transformer–rectifier type. These HVPS take their primary energy from the output of the generator, and are coupled to the acceleration grids through existing tetrodes that operate as a switching device.
The HVPS are capable of operating at a maximum voltage of 45 kV DC with load (56 kV with no load), with a maximum current of 120 A. The design duty cycle is 3 s pulse every 30 s.
Each HVPS includes a step down autotransformer, two rectifier transformers, two rectifier diode bridges, and a HVDC line to the TJ-II building. The regulation unit includes the capacitance filter, the crowbar element and the switching device (two tetrodes in parallel).
The autotransformer has a tap changer with 17 steps 400 V each, together with the position of a set of no-load switches to the output of the rectifier bridges. It allows the plasma grid (voltage level of the ion source) to operate at a voltage between 11 and 45 kV. It has short circuit withstand capability related to the protection system of the generator in which a set of Pyro-breakers limit the generator output current to 10 kA (peak value) to avoid high transient currents in the whole System. Therefore, the autotransformer has been designed to withstand 10 kA for 1 s. It is also protected against over-voltage produced by switching transients.
Two rectifier transformers are connected at the output of the autotransformer. When the rectifiers are in series, the system provides a twelve-pulse ripple in the DC line and the voltage available is the maximum. Although the transformer ratio is 15/20 kV, the two secondary are insulated up to a level of 72.5 kV in account of the series connection of the rectifiers. Their

windings must withstand a short circuit current of 1300 A for 1 s. In the secondary windings, a set of surge arresters have been installed between phases to protect against over-voltages.

Each diode rectifier is composed of six branches. A branch is composed of 24 diodes, with their heat sinks connected in series. Equalizing and snubber circuits are mounted in parallel to each diode. The rectifiers are cooled by unforced air. The diodes can withstand the short circuit conditions if a failure occurs downstream the rectifier, or if a number of crowbar operations are produced per day.

The system can be operated with one or two rectifiers, depending on the particle energy requirement. A set of no load switches allow commutation between the two modes. Commutation must be performed with low voltage (1.5 kV) at the 15 kV bus-bars in order to avoid excessive transient currents in the switch. The rectifiers can be decoupled from the DC line through another no load switch.

The high voltage DC line connects the rectifiers to the NBI area via a coaxial cable of ≈125 m length. Matching impedances are located at both ends of the line. In the NBI area, close to the torus hall, a switch connects the line to ground for safety reasons. A current measuring device, located in the low voltage pole of the line, detects abnormal conditions in it. A voltage divider is used to measure the voltage at the output of the transmission line. The crowbar device, the limiting resistors, and the fast switching elements are located also in the NBI area. The crowbar short-circuits the power supply in case of faulty operation of the switching elements that must cut the current to the ion source and the acceleration grids. The limiting resistors limit the short circuit current at the generator during crowbar operation to a value of 3400 A (peak). If a breakdown at the grids of the ion source occurs, the tetrodes should switch off the current in around 4 μs [24].

Chapter 4

The entire component of the rectifier system

4.1 Introduction

In general, the 7 converter sets have almost identical topology, each one with different power level, so we will refer to one general, but there are few differences between them.

There are three major differences; the first one is that the TF coil has three set of rectifier bridge in parallel instead of one for the others. This is due to the high rating current of TF coil (32.5 kA) that can not be supported by a single bridge so TF´s converter has 36 thyristors instead of 12 thyristors for the other coils. The second one is that HX1 and HX2 have the possibility to connect in series and power by different combination of their rectifiers. The last one is that the power rectifier transformers of CC, HX1, and HX2 have possibility to change their primary to Y-connection instead of Δ-connection in order to lower the voltage and also to reduce the ripple of the output DC current of rectifier.

The rectifier system consists of a power unit and a control unit. Control unit is installed in the rectifiers control room, whose major feature is the use of a DSP processor, providing the opportunity to work at very high speeds (real time). This control system is responsible for governing the power rectifier, sending fibre optic pulses to fire the thyristors. The power unit consists of the high-voltage elements of the converter set. It provides the conversion of motor generator power to the coils of TJ-II [25].

4.2 The power unit

The power unit contains: two sets of 6-pulse thyristors with de-ionized cooled water; which is described in the pervious chapter, interface reactor coil, zero-flux current transformer for current measurement. There are some boards are from the control unit but they are located close to the power unit. These boards are interface type B, interface type C, interface type D, the power supply board. Figure 4.1 represents the components of the power unit of the converter set and these boards.

4.2.1 Interface reactor coil

The two branches of the two 6-pulse thyristor rectifier are joined at the negative output by an interface coil that balances the output current of both branches getting a rectification reference to the output. The characteristics of the interface coil depend on the current rating of each coil as described in table 4.1. Its output connected to TJ-II coil.

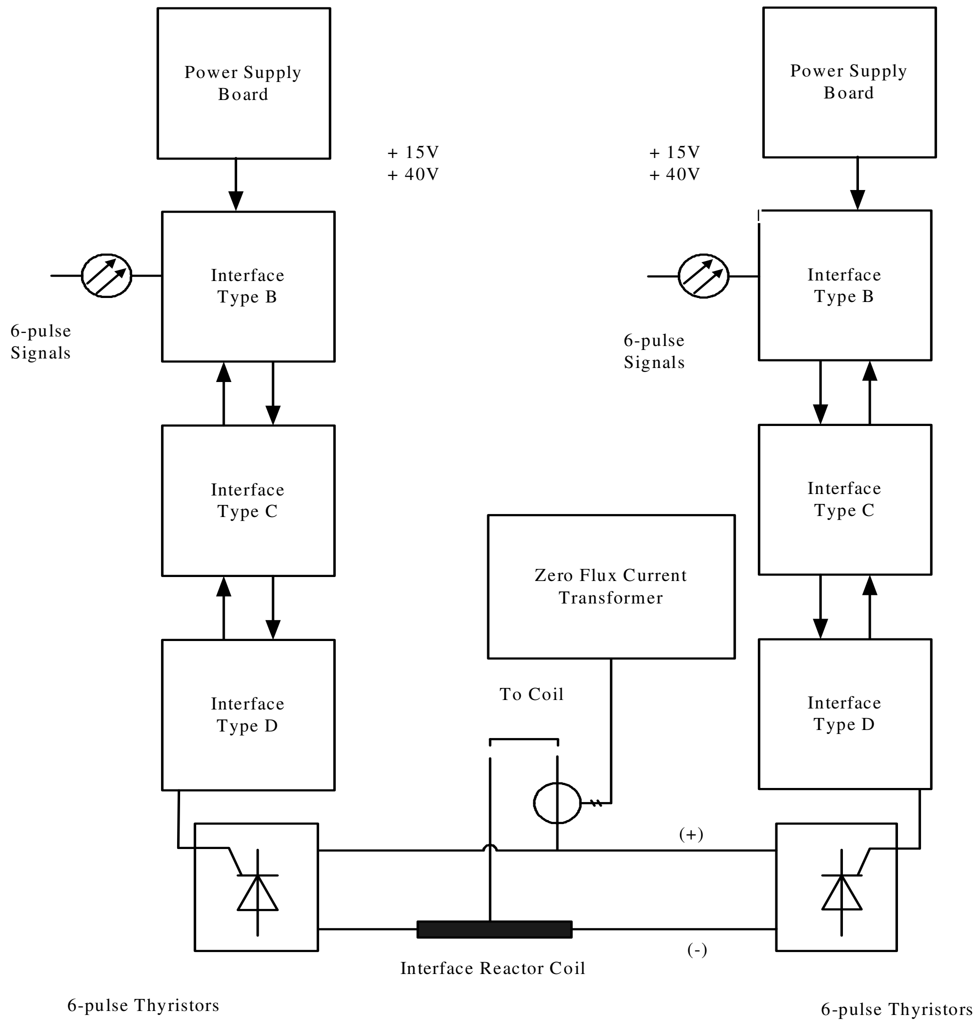

Figure 4.1: Schematic diagram of the power unit of the converter.

Coil	Reactor coil resistance (mΩ)	Reactor coil inductance (mH)
TF	0.141	0.348
CC	0.495	1.074
VF	0.400	0.655
HX1	0.400	0.655
HX2	0.343	0.489
OH	0.315	0.349
R	0.354	0.222

Table 4.1: The characteristic of the interface coil for the different rectifiers.

4.2.2 Zero-flux current transformer (ZCT)

For the DC current measurements, the power unit has the ZCT systems of FOELDI Company. But the TF coil has HITEC. They have a precision of 0.01% and an output signal band-width from DC to 20 kHz. The latter is necessary to measure the harmonics contained in the DC current. This system has the zero flux principle.

The zero flux principle has been applied for high precision current transformers for several decades. This is based on the compensation of the magnetic field generated by the current to be measured in a toroidal ferromagnetic core (measuring head) by a flux equal in magnitude but opposite in sense. Figure 4.2 shows the principal circuit diagram of a ZCT.

The Zero flux detector forms a very important part of the current transformer. Its function is to sense even the smallest residual flux in the magnetic core K1. Sensitivity, long term stability and low temperature coefficient of the output signal U_{DC} of utmost importance for the zero flux detector. The output signal U_{DC} of the zero flux detector is proportional to the resulting flux in the core K1 in a limited range, while its polarity gives the direction of the residual flux. The output U_{DC} of the detector is used to control the compensating current Ic through the windings Nc and the burden resistor R_B via the integrator Is and the amplifier A. In consequence the following equation applies for the zero flux condition:

$Ip * Np = Ic * Nc$

In general Np = 1, consequently: $Ic = Ip / Nc$

Thus the compensating current becomes an exact image of the primary current (with regard to magnitude and also to polarity) and can be measured as the voltage drop on the burden resistor. The specification of the ZCT depends to a very high degree on the quality of the burden resistor. In this respect; long term stability and the temperature coefficient are the most important specification. For this reason the ohmic value of the burden resistor is always chosen as small as possible to avoid the influence of dissipation on the resistance.

Consequently the voltage drop on the burden resistor is relatively small and has to be amplified to 10 V output signal for rated current. The output amplifier B has sensing outputs and is of highest quality. AC components of the primary current Ip or sharp current ramps cannot be measured with high sensitivity by the zero flux detector which is inherently a relatively slow-acting device.

Because of this, a second core K2 is added which works as a simple AC Current Transformer. Suddenly changes in the primary current generate a voltage signal U_{AC} in the winding N_A. It passes the amplifier I_F and is then added on the input of amplifier A to the amplified output signal of the zero flux detector. The current transformer will be saturated (the proportionality between the output voltage V_{OUT} and the current to be measured is lost) if the primary current exceeds 125% of the rated current or under fault conditions of the electronics. This device is used for measuring the output DC current of the converter.

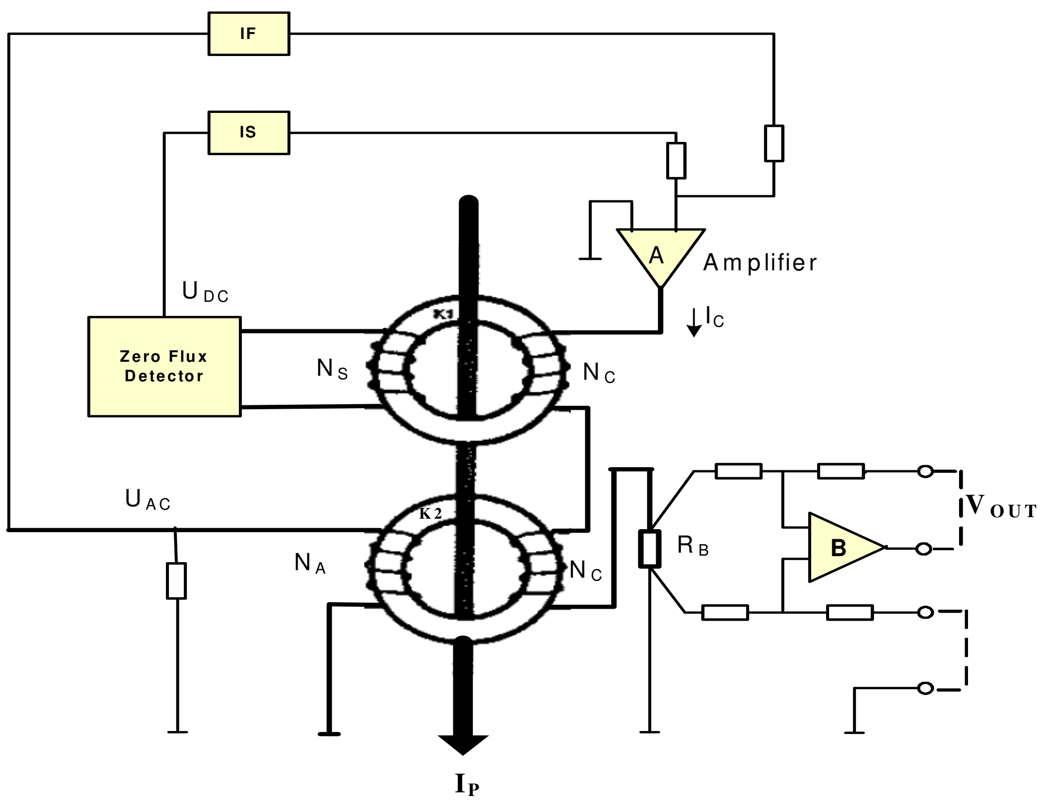

Figure 4.2: The zero flux principle of the DCCT.

4.2.3 Power supply board

There is a power supply for each rectifier bridge; one for the secondary-delta transformer branch and the other for the secondary-star transformer branch. this power supply transform 3-phase AC to DC for supplying the interface type B and D. the input of this board is 380 Vac phase – to-phase while the output is +40 Vdc with 5 A and +15 Vdc with 1 A. This output which has the same reference voltage, is necessary to supply the pulse which coming from the control unit to the power semiconductor. This board feeds the interface type B and C through 24-pin data cable. This board has a relay to switch off the circuit during any failure.

It takes its power from UPS through a characteristic transformer 380/380Vwith power of 250 VA that brings an isolation voltage of 6 kV minimum.

4.2.4 Interface type B (optical/electrical conversion board)

This interface receives 6-pulses from the control unit (interface type A) via optical fibre cables. There are two interfaces board of this type; one for the secondary-delta transformer branch and the other for the secondary-star transformer branch. This interface is used for converting the light signal from the control unit to an electrical signal to trigger the thyristors.

This interface receives its power from the power supply board through a 24-pin data cable. It receives +15 Vdc to supply its electronics and +40 Vdc to supply 4 firing circuits type C. The output of this interface can feed 4 thyristor-bridges in parallel with a gap of less than 1 μs through a 40-pin data cable. This interface board is used to feed three bridges in case of TF coil and the fourth one is a spare one it is used to feed one bridge in case of the other coils and the other three spare parts. This card has a function to chopper the signal with modulated mode on/off at frequency about 16-20 kHz to be sure that the gate of the thyristor has been triggered during the pulse.

Any failure detected in the optical/electrical conversion or in the supply power will be transmitted to the control unit (interface type A) via an additional optical fibre cable. So two electrical signals (one for each board) are converted into optical signals to indicate a possible anomaly to the interface type A and then to DSP.

4.2.5 Interface type C (Firing pulses amplification board)

This interface receives a 6 low-power pulse signals from the interface type B via 40-pin data cable. This interface is used to amplify the low-power signal into 40 V/4 A signal to be ready to drive the gate of the thyristor. This interface can feed one bridge; so TF rectifier has six of this board. This interface receives the necessary power (+40 Vdc) from the interface type B through a 40-pin data cable.

Any failure detected in the amplification process or in its supply power will sent to the interface B and then to the control unit.

4.2.6 Interface type D (Firing pulses isolation board)

This interface receives the 6 pulse signals from the interface type C via 40-pin data cable. This interface can feed one bridge so TF rectifier has six of this board.

The signals are used to trigger the gate of the thyristor by applying these signals between gate and cathode. The cathode has a high power so the control signals should be isolated from this power. So this interface is used to isolate the amplified firing signal from the thyristor (high power part).

This interface contains 6-pulse transformers with minimum isolation of 4000 V to introduce the amplified firing signal.

Any anomalous lead connection detected in the firing process will be sent to the interface C, B respectively and then to the control unit.

4.3 Control unit

The rectifier's control cabinet is physically separated from the thyristor bridges. The firing pulse signals are transmitted through fibre optics.

The control unit contains (see figure 4.3): DSP, PLC, interface type A, interface type F, interface type I, A/D converter, display board, power supply board, and other small boards for signals management. The control unit regulates the operation of the converter set; especially converter and synchronize the firing of the thyristors.

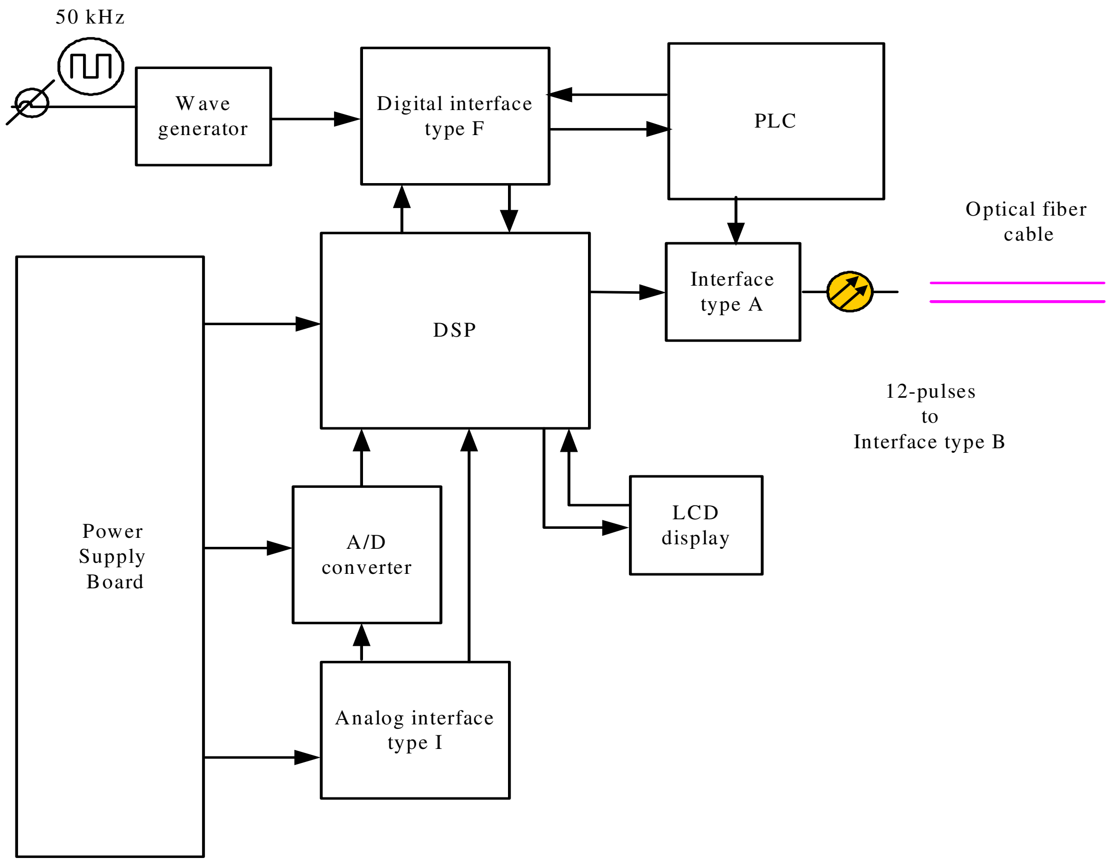

Figure 4.3: Schematic diagram of the control unit of the converter.

4.3.1 DSP

The regulation and the control logic are implemented on a DSP (TM3200C51). A 80C186 microprocessor deals with the data base, events storage, parameter display and serial port communication tasks. A dual port RAM is shared by the DSP and the microprocessor to improve the communication speed between both devices. Four FPGA generate firing pulses, control the DMAs and the system synchronisation. Normal zero-crossing detection is very slow for this system (with drop of frequency from 100 Hz to 80 Hz in one second). An algorithm based on the product of the input Vac waves and sinusoidal references provides a much faster response. Using this variable frequency for the DSP timing, it will be possible to allow optimal filtering of the rectifier harmonics.

There are specific controller routines for the normal operation and the stop operations. Three possible stop sequences (normal stop, emergency stop and freewheeling) are considered. The normal stop provides a linear ramp down of the current till zero value, during this ramp-down, the output voltage of the rectifier will reach negative values. The emergency stop shifts the firing angle to its maximum value, to extinguish the current in the coil with a negative voltage. The total stop sequence inhibits the firing pulses. The freewheeling stop fires all the thyristors at a time if the AC breaker opens. By this way, the system prevents over-voltage and limits the risk of having the coil current flowing through two thyristors legs which could lead to junction overheat.

Figure 4.4 shows the flow chart of the current regulation process on the DSP. The rectifier is controlled in current.

The $L * dI_{ref} / dt + R * Iref$ provides the value of the required output voltage depending on the current reference given to the system. During the experiment the resistance will change with the temperature. In order to compensate the consequent error and other disarrangements a PI control corrects the drift between feedback and reference. The coupling between the coils is compensated by current reference feed-forward inputs.

$M_j * dI_{j,ref} / dt$ defines the required voltage correction to be operated to obtain the required output current.

Both derivative controls $L * dI_{ref} / dt$ and $M_j * dI_{j,ref} / dt$ improve the response time. However, derivative controls are very sensible to input noise which could lead to a relative loss of accuracy. In order to prevent this problem and bearing in mind that the maximum accuracy is required when the current references are constant, the derivative loop is disabled when its value does not exceed an adjustable threshold. The voltage reference which is a constant adjustable by the operator represents the maximum allowed voltage.

This voltage loop will prevent the rectifier to apply a voltage higher than the allowed. The DC voltage is required to obtain the firing angle by means of the Arc Cos table. This way the system has a linear behaviour and accuracy will be improved. In order to compensate AC voltage variations, the applied Arc Cos function is related to the AC voltage amplitude. Two 6-pulse bridges working in parallel through an iron core interphase reactor need a special solution for the current balancing. The delay pulses to slave bridge permit the synchronisation between the master and slave rectifiers under the same configuration.

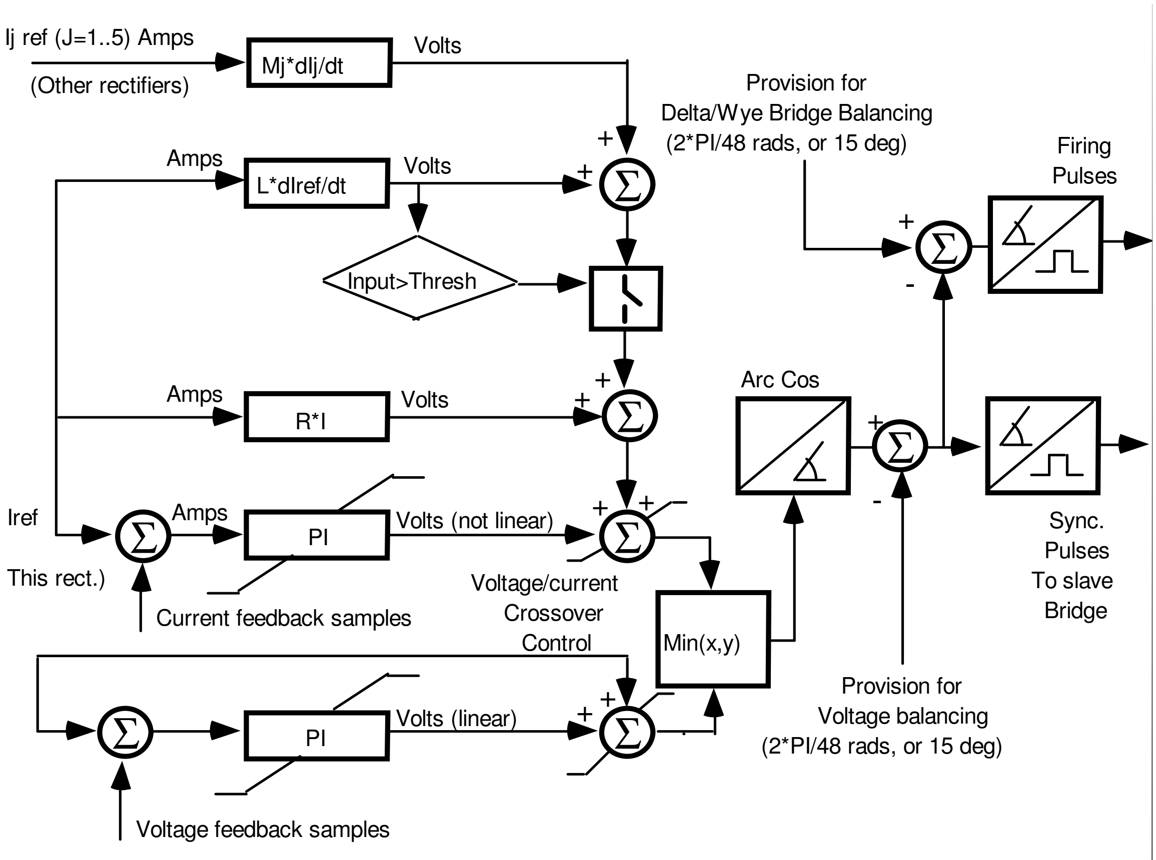

Figure 4.4: TJ-II Precision Rectifier Control System.

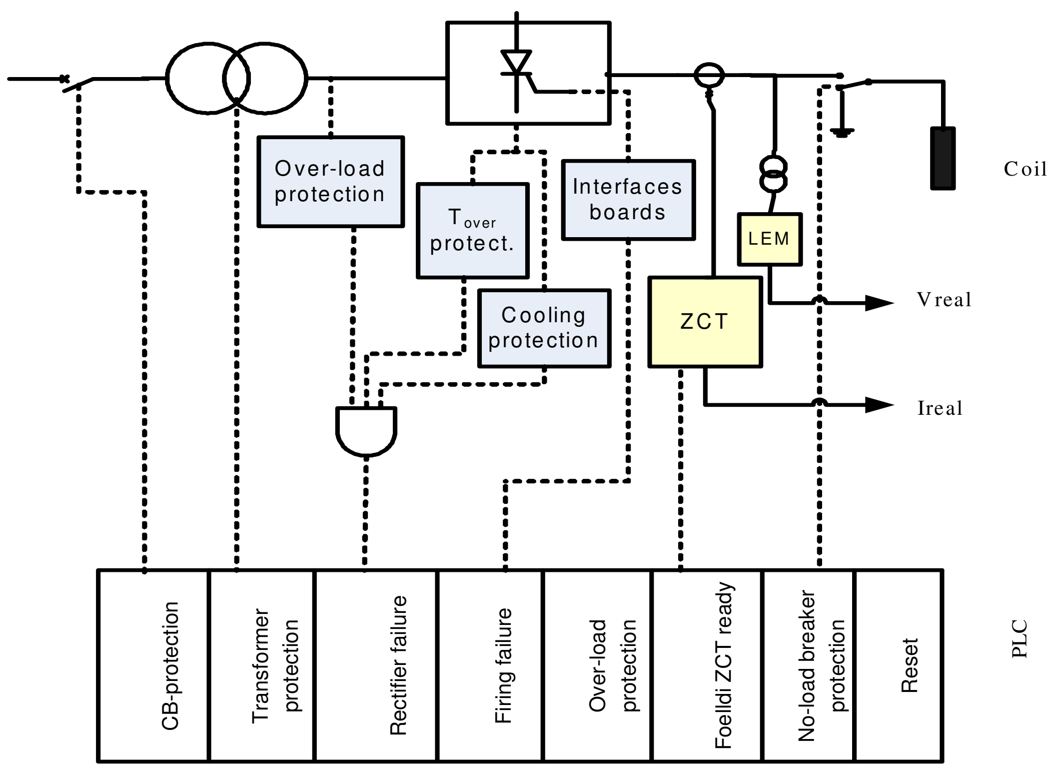

Figure 4.5: Schematic diagram of the converter's protection signals.

4.3.2 PLC

The control system has PLC type S5-95U SIEMENS with the basic configuration of 16 digital input, 16 digital outputs, 8 analog inputs, and 1 analog output. Also it has an expansion of three modules; each one has 8 digital inputs. PLC is supplied via UPS through transformer 220/24 V where all signal of PLC supplied by 24 V. The 24 V supply has PLC entrance signal to verify that there is always control voltage. This signal activates the output of the PLC to excite a relay whose contact activate the presence voltage signal in the general control system.

PLC shares the programmed logical information with the digital interface type F and the General control system to control the operation of the converter.

The status of the power transformer, thyristor, DCCT ready, CB status and no-load breaker signals are connected to the input of the PLC (see figure 4.5). These signals are duplicated, one to the PLC and the other to the general control system. Also it is connected to firing process failure and Reset bottom. While the output is connected to ready for the general control system, inhibit the firing pulses that goes to interface A and open/close freewheeling process.

4.3.3 Interface type I (Analog signals board)

This interface exchanges the analog signals with DSP, A/D converter and Rectifier control system. The function of this interface is to adapt the analog inputs of various elements of the converter set and the General control system to acceptable levels for the Rectifier control system. This interface communicates with the DSP via data cable.

It is supplied by a power supply of 24 Vdc with a maximum ripple of 5%. This voltage is transformed to +/- 15 V to feed dc/dc converter which also feeds the interface type F and +/- 6 V to supply the other component. The average current absorbed by all cards which depend on the 24 Vdc is ≈450 mA. The signals which are exchanged in the analog interface are described in the table 4.2. The analog signals include DC current and voltage measurements, voltage limits, the current reference, the current reference from the other converters and AC voltage and current measurements. Certain signals processed in the analog signal interface are converted to digital signals before going to the Rectifier control cabinet, therefore it includes 16-bit A/D converter interface before the Rectifier control system. These signals are the real DC and the reference current.

4.3.4 Interface type F (Digital signals interface)

This interface fits the digital signals exchanges with the Rectifier control system to be processed. The function of this interface is to adapt the digital inputs of various elements of the converter set, PLC, and the General control system to acceptable levels for the Rectifier control system. It can be divided into two types according to their application: one that receives signals, which are delayed before the adaptation by using a filter and the other is electrical and optical signals that pass directly to the control. This interface communicates with the Rectifier control system via 16-pin data cable. It is supplied by +/- 15 Vdc and 220 mA max. For the adaptation process, three levels of voltage are generated (15, 12, 5 Vdc). The signals which exchanged in the digital interface are described in the table 4.3.

Signal name	From	To	Description
DC Output voltage (Vdc)	Rectifier output	DAS, general cont., int. I, and DSP	This signal is the measurement of the output voltage of rectifier given by a LEM potential transformer with a precision of 1%.
DC Output current (Idc)	Rectifier output	General cont., int. I, DAS and DSP	This signal is the measurement of the output current of rectifier given by a ZCT current transformer with a precision of 70 ppm.
Voltage limit	general control	Int. I and DSP	General control system introduces an output voltage limit for each rectifier.
Current Reference	General or fast control	Int. I and DSP	General or fast control system introduces a reference current for each rectifier to follow it.
Current reference of the other coils	General or fast control	Int. I and DSP	This signal is used to estimate the mutual inductance between the coils.
AC voltage measurement	Sync. transformer	Int. I and DSP	This signal is the output voltage of the synchronous transformer.
AC current measurement	Rectifier transformer	Int. I, DSP & general control	These six signal are the measurement of the primary currents of the rectifier transformer.

Table 4.2: the analog signals of the converter set.

Signal	From	To	Description
Breaker status	breaker	PLC	These signals are introduced to the rectifier control system and report the status of the CB (open, close, grounded, triggered ...etc).
Mode selection	Operator	Interfaces I and F	High level indicates that the signal is sent from the fast control (mode C) while the low-level indicates that the General control system controls the reference (mode A).
AC voltage selection	Operator	Interfaces I and F	The high-level indicates that the output of the generator is 15kV while the low level indicates that the output is 1.5kV (mapping mode of operation).
Frequency selection	Operator	Interfaces F	The high-level indicates that the frequency is 100 Hz while the low-level indicates that the frequency is 50 Hz.
Run/Stop	General control system	Rectifier Through PLC	If the whole system is ready for operation, an output signal goes from the General control system to rectifier to follow the reference current through a PLC output.
Reset	Hardware	General control system, Interface type A and PLC	When an alarm appears in some component of the converter, it can not be started until the resolving of the problem and the manual pressing of Reset bottom.
AC over-voltage in the load	AC Over-voltage detector in the Rectifier	rectifier control system and PLC	Any AC over-voltage will sent doubled signal: one to PLC to avoid the starting of the rectifier working or stop its operation, and the other to the rectifier control system.

No-load breaker status	No-load breaker	PLC	These signals inform about the status (open, close, ground…) of the no-load breaker.
Free-wheeling	PLC	rectifier control system, Int. F and DSP	If the CB receives the order to open, the PLC sends a signal to activate the freewheeling process.
Power transformer status	Power transformer	PLC and general control system	This signal informs the PLC and the general control system about the status (temperature, Buchholz relay …) of the power transformer.
Thyristor status	thyristor	PLC and general control system	A double signal goes to PLC and general control system to inform the status (cooling, over-temperature, DCCT ready…) of the thyristors.

Table 4.3: the digital signals of the converter set.

4.3.5 Interface type A (Electrical/optical conversion board)

This interface receives the trigger pulses from the DSP and transmits them to the interface type B via an optical fibre cables. There are 12 pulses signals transmitted to two interface type B and it receives two light signals which inform the status of the two interfaces type B, C, and D; one from each branch. This interface is used for convert the electrical signal from the DSP to light signal to trigger the thyristors. It uses an optical fibre cables to isolate the control unit from the power unit, so there is not any electrical connection between the two units.

This interface receives its power from the power supply board through a 30-pin data cable. It receives +5 Vdc to supply its electronics and the control signal from DSP. The output of this interface is connected to relays that can switch off the thyristor when any failure happens in the firing process. This board also informs the control system that the thyristor is ready for operation and the pulse is in correct situation.

This board has a rest bottom that can be pressed to get a reset.

Chapter 5: Measurements and results

The aim of my work is to study the characteristics of all the power and control circuits of the radial field rectifier, to check the operating conditions of the different control boards and to put into operation the whole system. Firstly, it is required to test the interface boards A, B, C and D that take 12-signals from the current controller (DSP) till the gate of the thyristor. Secondly, after investigation that these boards are in proper condition, a test will be done with a Dummy load. This load has a possibility to change its parameters to be similar to the Radial coil. Finally, after investigation that the power supply works properly, a test will be done with the real TJ-II coil. This test will be done with R-coil alone and with all TJ-II coils.

The instruments that is used in the tests:

- Oscilloscope Tektronix.
- Signal generator
- Two DC power supplies: one has a 0-30 Vdc and the other has a 0-60 Vdc.
- Yokogawa DR1400 oscilloscope recorder 350 Vpeak max.

5.1. Boards test [26]:

5.1.1. Interface type A test

This card receives 12- pulses from DSP and it converts them into optical signals. These signals are transmitted to the interface type B via optical fibre cables. The test of this circuit is done by connecting 5 Vdc and 12 V pulse with a frequency of 100 Hz as input as shown in figure 5.1. This figure shows a schematic diagram of the electronic circuit that represents one channel.

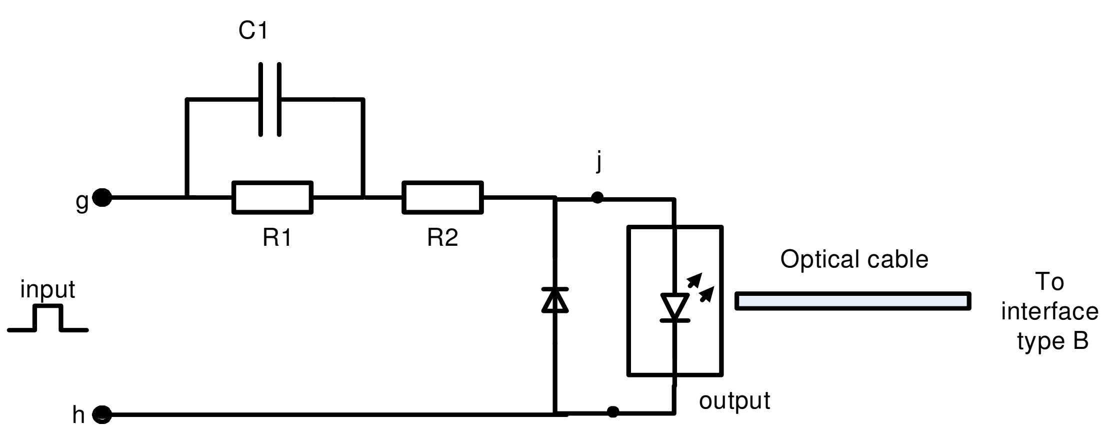

Figure 5.1: Electronic circuit represents one channel of the interface type A.

This board has a protection system that informs DSP about any trip in interfaces type B, C and D.

Figure 5.1 shows the electronic circuit that represents one pulse channel. The test of this circuit is done by connecting 12 V pulse with a frequency of 100 Hz to the input (between points g, h) in figure 5.1 and the oscilloscope is connected to the output (between points j, h). It observes that the outputs of the 12 channels are identical as shown in figure 5.2 and there is light emission for each channel when the input voltage is connected to its respect connectors. Also a trip is simulated and it gives a trip signal as output to the DSP. After the investigation and the test of this board, it was worked properly.

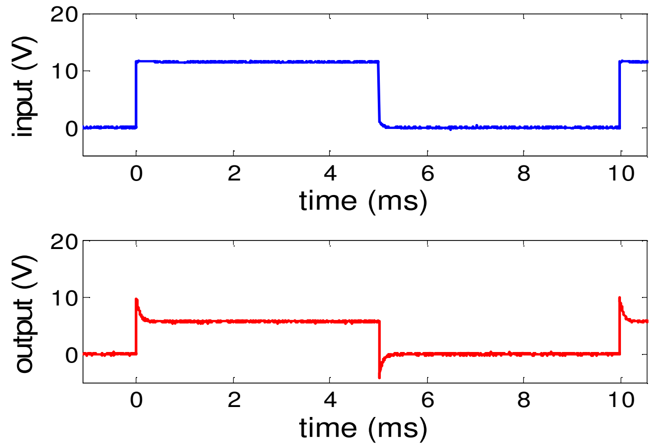

Figure 5.2: The input and output voltage of the interface type A.

5.1.2. Interface type B test

As mention in the pervious chapter, the interface type A transmits the 12-pulses into two interfaces type B via an optical fibre cables. Figure 5.3 represents the electronic circuit for one-pulse channel.

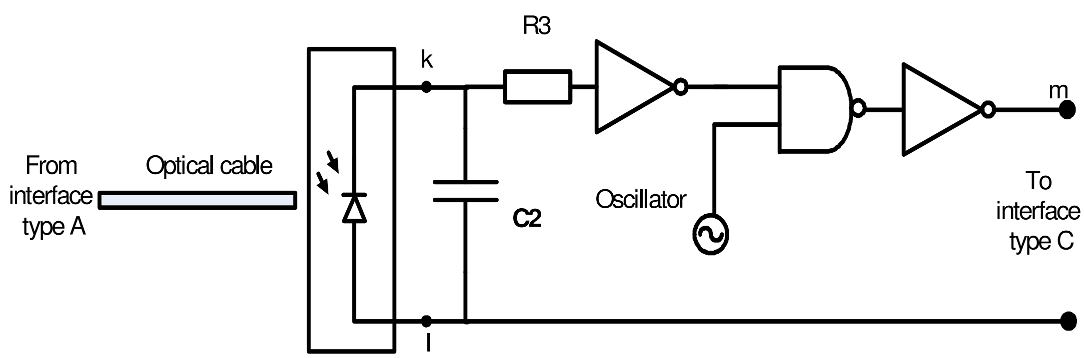

Figure 5.3: Electronic circuit represents one channel of the interface type B.

The test was done to check that the frequency results from the oscillator when connecting 15Vdc without input voltage, is about 16 kHz.

With connecting the interface type A, and the optical fibre cables to the input of this interface: it is observed that the output as shown in figure 5.4 is 15 V pulse signal and it is modulated with a frequency of 16 kHz.

Two boards have been checked; each one provides 6-identical channels. And the results are identical for the 12 channels.

The failure process has been checked for the failure of the power supply and the failure of the interface output. This failure send an optical signal to the interface type A and then to the control system to inform the control to stop the firing process.

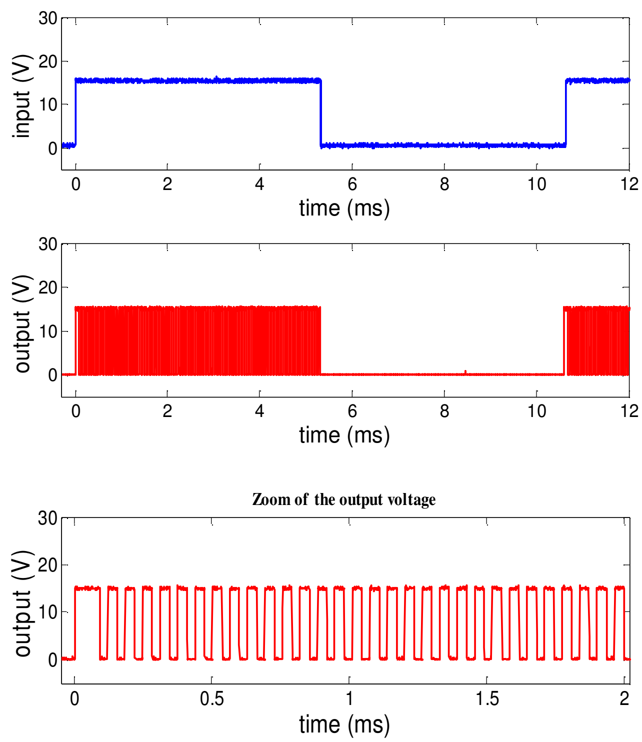

Figure 5.4: The input and output voltage of the interface type B.

5.1.3. Interface type C test

This board has six identical independent amplifiers channels. Each one has to increase the power of the pulse up to a sufficiently high value to turn-on the thyristor

Each channel based on power transistor to amplify the input signal of the interface type C to a level suitable to drive the thyristor gate.

There are two supplies (see figure 5.5); the first is 15 Vdc that used to feed the electronics in general (six error detectors) and another supply has to provide with the power the output circuit feeding the six amplifiers in separate way. The output parameters of the pulse are: maximum voltage up to + 40 V and a current could be up to 4 A maximum, depending of the impedance of the load. To ensure a normal operation in the signal processing of this card, a signal is measured for each output of the amplifiers at the collector of the transistor amplifier.

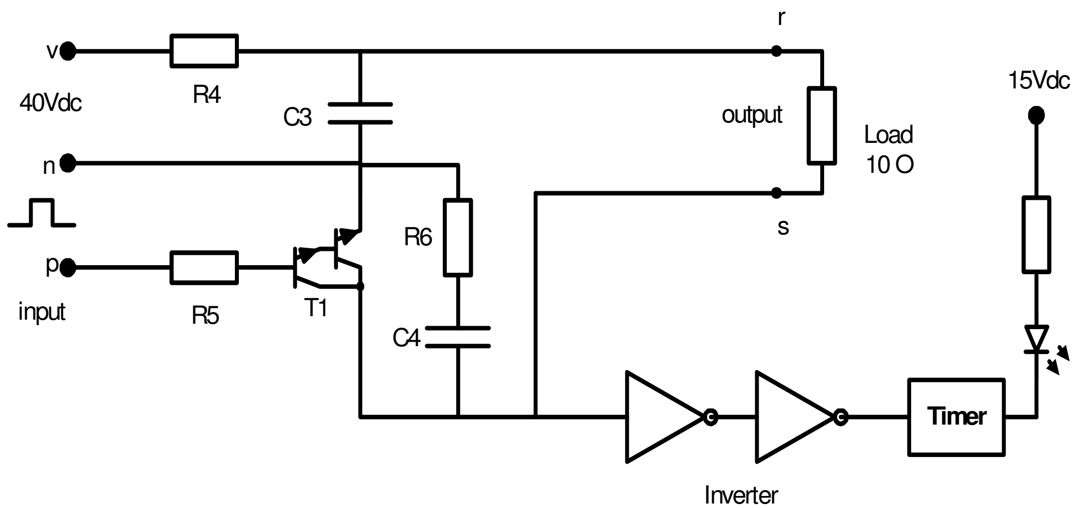

Figure 5.5: Electronic circuit represents one channel of the interface type C.

This signal processing is to detect the lower edge of the signal (through inverter with Schmitt trigger); then starts a timer of about 20 ms, during which its output does not change state. The time of 20 ms becomes zero every time it gets another impulse and refreshes start of counting.
The requirements for test this board: two DC power supply (15 Vdc and 40 Vdc), wave generator gives a pulse with 15 V amplitude and 100 Hz frequency with 1/5 duty cycle.

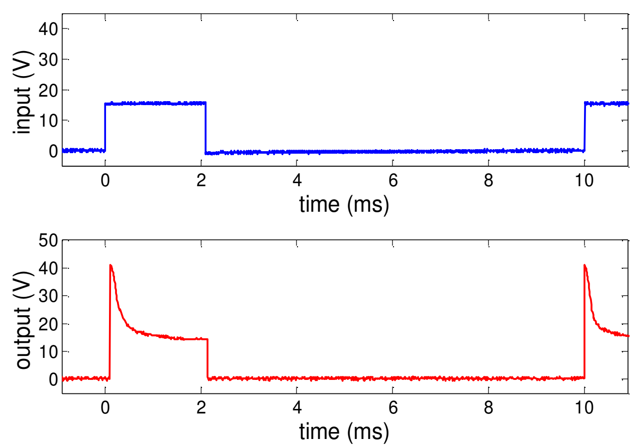

Figure 5.6: The input and output voltage of the interface type C.

The test of the two boards type C has been done. Firstly, the output of the amplifier gives zero volts and the LED does not switched off.

The investigation of this card shows a broken NE556 dual-timer IC-chip in one interface board. For the other board, the investigation shows a broken HEF4068DB 8-input NAND gate IC-chip.

After changing these two ICs, an output signal has been observed as shown in figure 5.6. This signal has a voltage close to 40 V at beginning of the pulse and falls down to 15 V at the end of the pulse.

If any failure happens for one amplifier or its load, the corresponding LED will switch off. But if a series of failures happens at the same time, an output signal will sent to the interface type B that indicate to abnormal operation.

5.1.4. Interface type D test

This board provides galvanic isolation between the control and power part of the rectifier and it contains six equal pulse transformers. These transformers has the high isolation level between primary and secondary winding about 4 kV and maximum current of 4 A. Also this board has a protection circuit which detects a failure of any of the six firing pulses and the trip signal is sent to the interface type C. The isolation of the transformer has been tested.

Thyristor No.	**Delta -branch**		**Star-branch**	
	$R_{G\text{-}K}$ (Ω)	**$R_{A\text{-}G}$ (kΩ)**	**$R_{G\text{-}K}$ (Ω)**	**$R_{A\text{-}G}$ (kΩ)**
V1	23.9	52.8	11.3	80.1
V2	25.6	54	9.5	79.3
V3	27.1	52.8	10.6	80.1
V4	26.4	50.8	10	79.3
V5	23.8	52.8	10.4	79.9
V6	24.3	53.9	8.9	79.3

Table 5.1: Thyristor resistance measurements.

Also the resistance of the 12-thyristors has been tested to check that the thyristors are in good conditions. Table 5.1 shows the result of the thyristors measurements. The difference in the two branches is because delta-branch thyristors are made by SEMIKRON while star-branch thyristors are made by SIEMENS.

5.1.5. Interface type I test

The test has done in this interface to insure that the noise level is in acceptable values. The noise amplitude of the real and reference current as shown in figure 5.7 are 3.8 mV and 2.2 mV respectively.

These values are less than 0.06 % of nominal values. And the amplitude voltage noise as shown in figure 5.8 is about 20 mV, i.e. less than 0.3% of nominal values. These values are acceptable in TJ-II measurements.

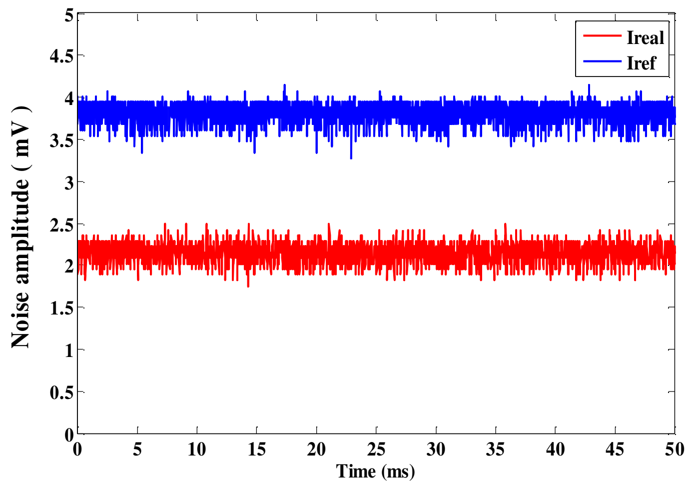

Figure 5.7: The real and reference current noise in the interface type I.

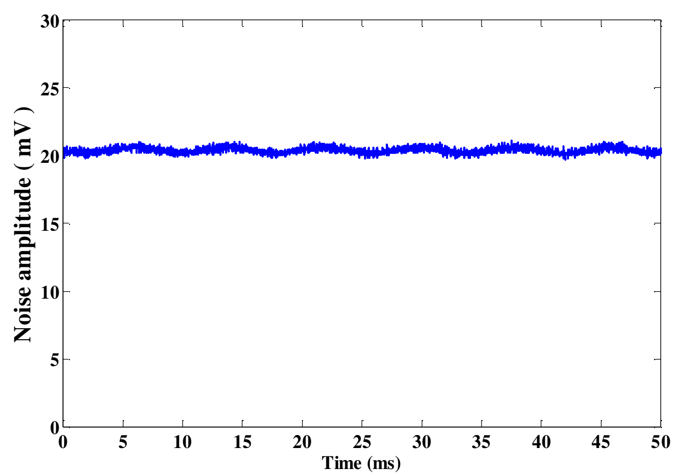

Figure 5.8: The real voltage noise in the interface type I.

After these board tests, the rectifier was ready for the current test with the dummy load to be sure that the whole rectifier system works properly.

5.2. The Dummy-load test

5.2.1. Dummy load

The dummy load consists of a group of five coils assembled concentrically one above the other and a water-cooled 32 stainless steel resistors connected in series with the coils.

The coils were provided by the Max Planck Institut für Plamaphysik (Germany). Their main characteristics are: weight: 3.4 ton; external diameter: about 2 m; nominal current: 40 kA; inductance and resistance: 1.1 mH and 1 mΩ respectively.

Depending on series/parallel connection of the coils and distance between them, the total inductance of the system is varied and it allows to adjust it for the required value.

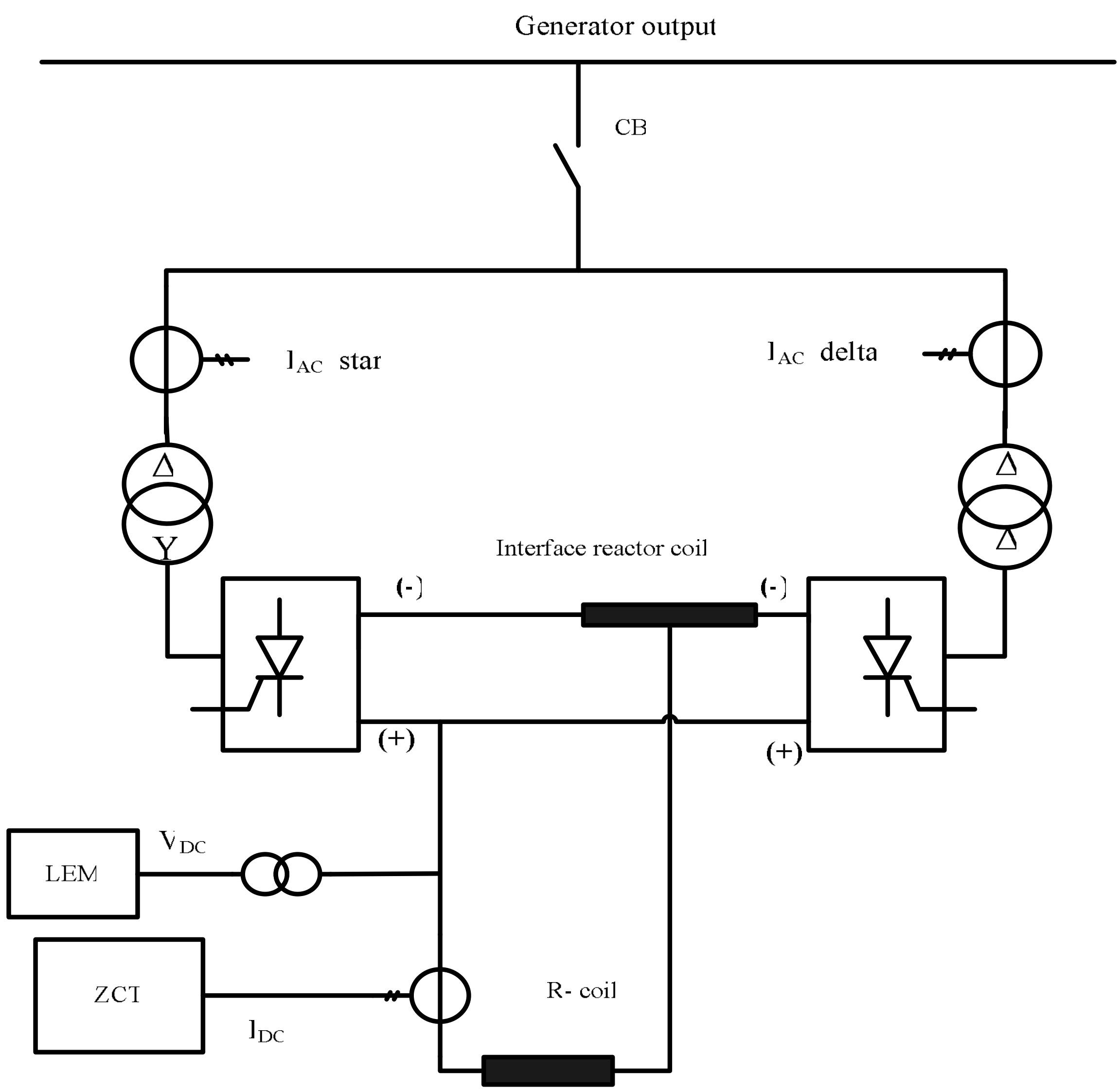

Figure 5.9: schematic diagram showing the electrical parameters that are measured.

With the 32 stainless steel resistors, it is possible to adjust the resistance from zero till a value of 83 mΩ. Therefore, it is possible to obtain the electrical parameters of the load (inductance and resistance) very similar to the real TJ-II coils system.

For the current test the dummy load parameters have been adjusted for the following values: resistance of 19.67 mΩ and inductance of 1.1 mH. These values are similar to the R-coil parameters.

The current test has a main objective to check the correct operation of the rectifier and its control system. The test has been carried out for two level of the flat top current of 2 kA and 5 kA. The current pulse parameters are following: ramp up time as 440 ms, stabilization time as 280 ms, flat top as 250 ms and ramp down time as 300 ms. The output current and voltage of the rectifier have been measured during the test. Figure 5.9 shows the electrical parameters that are measured.

5.2.2. Current test in the dummy load

The DC current that is measured by a ZCT transducer as shown in figure 5.10 and 5.11 follows the reference current value with some differences. These differences are increased in the case of an output DC current of 5 kA test because the parameters of the current controller (DSP) are not adjusted precisely for the dummy load.

A ripple in the real current has been observed as shown in figure 5.12. This ripple has a frequency of 12th harmonics (no. of thyristor pulses) of the output frequency of the output generator (90Hz). So the ripple has a frequency of 1100 Hz as shown in this figure with a maximum amplitude of ± 5 A, i.e., 0.25 % from the nominal current at 2 kA. This ripple decreases to about 0.16 % from the nominal current at 5 kA.

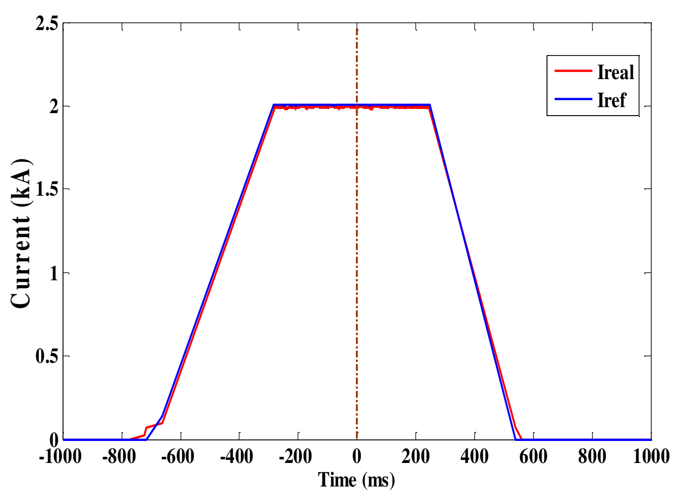

Figure 5.10: The real and reference currents in the dummy load at 2 kA.

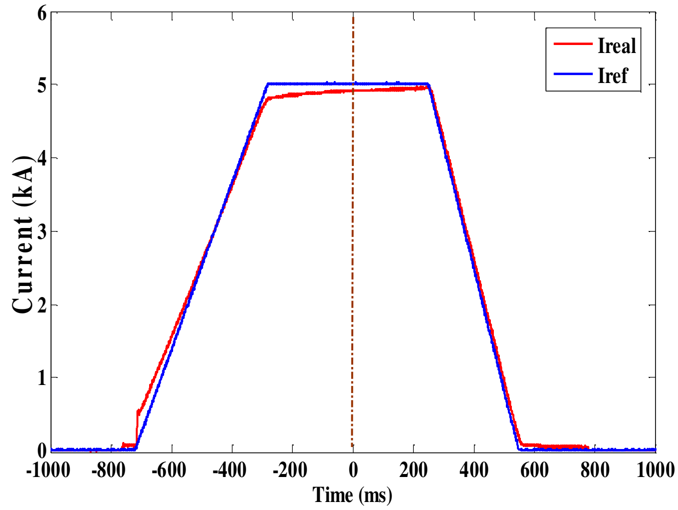

Figure 5.11: The real and reference currents in the dummy load at DC output current of 5 kA.

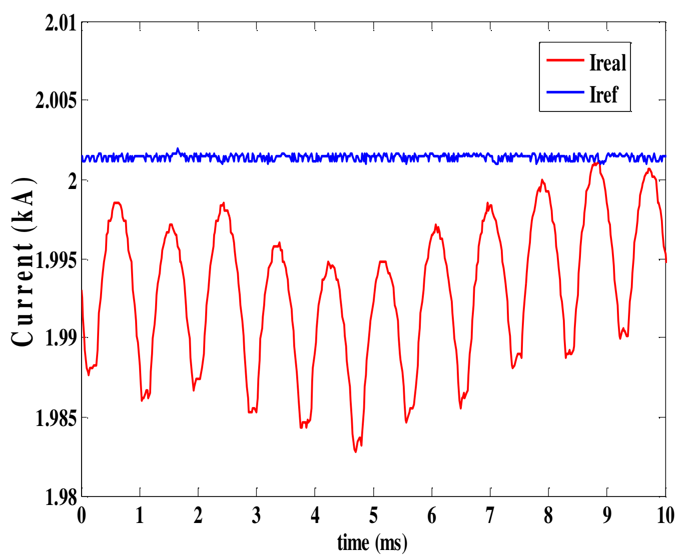

Figure 5.12: The ripple in the real and reference currents at DC output current of 2 kA.

5.2.3. Voltage test in the dummy load

The DC voltage is measured using a LEM transducer.

Figure 5.13 and 5.14 shows that the DC voltage follows the current profile because the dummy load is more resistive load. It has 12^{th} harmonic amplitude as 3% of the amplitude at the fundamental frequency.

These results of the dummy load test show that the radial field rectifier system is in good condition. So we will move to the final test with the TJ-II coils.

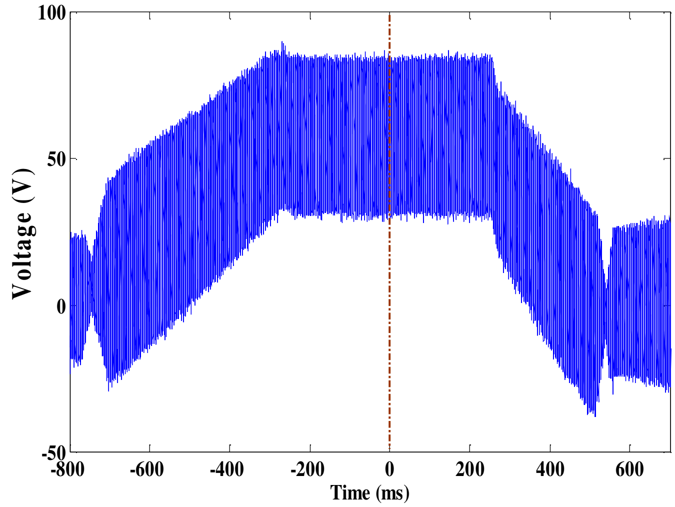

Figure 5.13: The real DC voltage of the dummy load at DC output current of 2 kA.

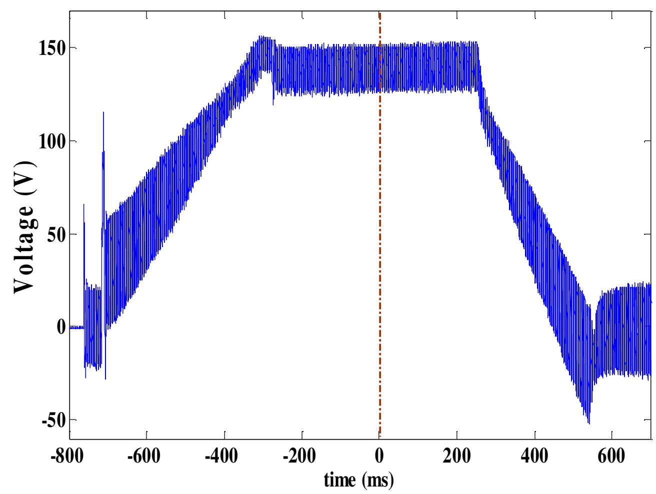

Figure 5.14: The real DC voltage of the dummy load at DC output current of 5 kA.

5.3. R-coil test

This test has been done with the R-coil alone and with the all TJ-II coils in order to check the effect of the mutual inductances. This test is done with different current values i.e. at 2, 3, and 4 kA.

In this test, two main measurements are achieved: voltage and current measurements. These measurements include the AC and DC measurements. This test has the following time consequence for the current profile: the ramp up time as 720 ms, stabilization time as 280 ms, flat top as 250 ms, and the ramp down as 300 ms. The R-coil has a resistance of 14.18 mΩ and an inductance of 0.97 mH with an isolation resistance of 40 kΩ to the ground.

5.3.1. Voltage measurements

In these measurements, the phase output voltage of the generator has been measured.

The generator has an output of 15 kVrms and speed of 1350 rpm.

Using the following relation: $f = \frac{p * n}{120}$ where **n** is the velocity of the engine, **p** is the number of pair of poles and **f** is the output frequency of the engine. So the output frequency of the generator is 90 Hz as shown in figure 5.15.

This voltage has measured during the operation of the all TJ-II coils with a generator pulse of 40 s as RMS value as shown in figure 5.16. This figure shows that no drop during the current pulse. The phase output voltage has a 3^{rd} and 19^{th} harmonics of about 2.6% of the value at the fundamental frequency as shown in figure 5.17. These harmonics are due to the NBI auxiliary system that is connected in parallel with all coils-converter system. The other harmonics have been eliminated due to seven sets of the 12-pulse rectifiers connected in parallel.

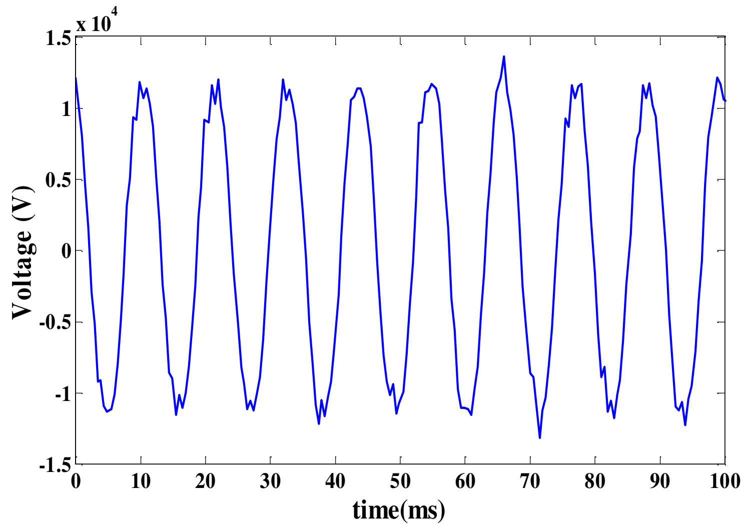

Figure 5.15: The output phase voltage at the output of the generator during the pulse.

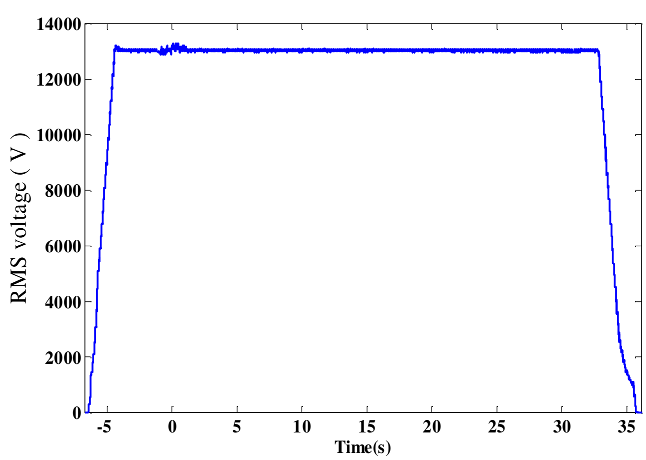

Figure 5.16: The output RMS voltage at the output of the generator during the generator pulse.

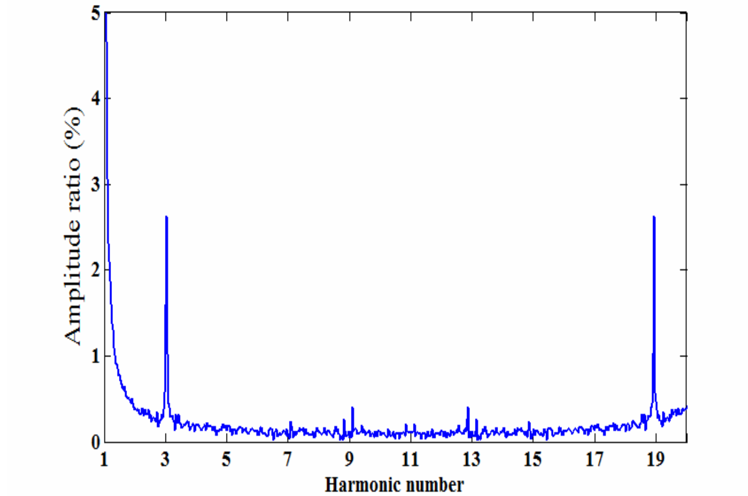

Figure 5.17: The output phase voltage harmonic at the output of the generator.

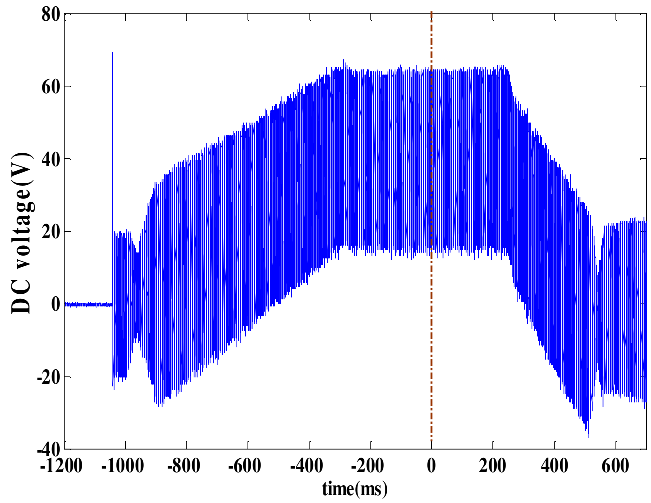

Figure 5.18: The DC voltage at an output DC current of 2 kA.

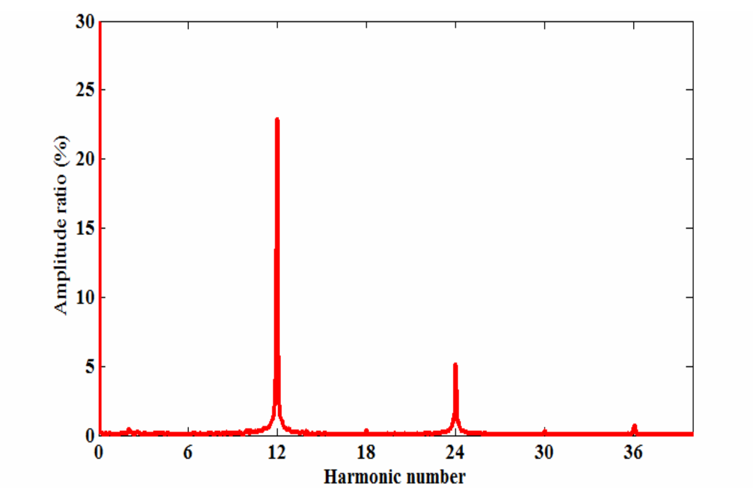

Figure 5.19: DC voltage harmonics at DC output current of 2 kA.

The DC output voltage measurement of R-rectifier shows a profile similar to the current profile because the coil is more resistive than inductance.

Firstly, with the output current of 2 kA, the voltage has 12th and 24th harmonics as 22% and 5% of the value at DC respectively as shown in figure 5.19. The voltage ripple is about ± 25% of the nominal value as shown in figure 5.18.

Comparison figures 5.13 and 5.18 shows that the DC voltage is lower in the case of R-coil than in the case of the dummy load because the R-coil resistance is lower than the dummy load resistance.

Secondly, with the output current of 4 kA, this voltage has 12th and 24th harmonics 5.2% and 1.35% of the value at DC respectively as shown in figure 5.21.

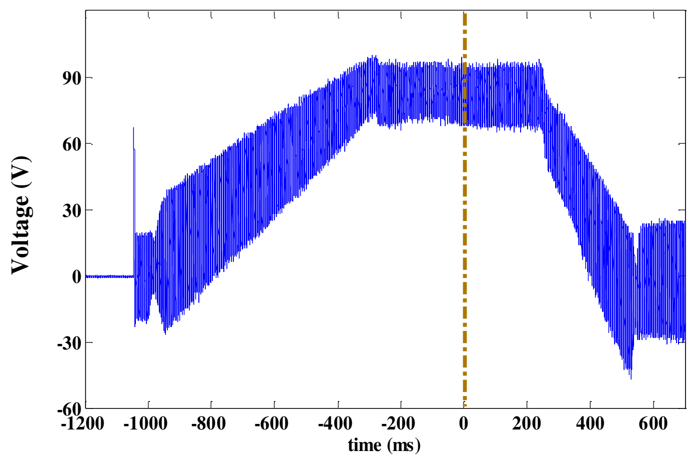

Figure 5.20: DC voltage at an output DC current of 4 kA.

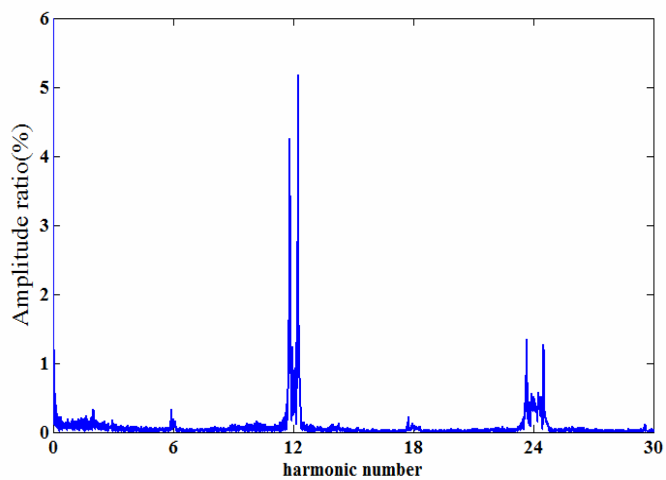

Figure 5.21: DC voltage harmonics at DC output current of 4 kA.

5.3.2. Current measurements

The current measurements have two measurements AC current and DC current. Firstly the AC current is measured in the primary of the delta/delta and delta/star power transformers using industrial current transformer. This current is 7.5 A at the output current of 2 kA as shown in figure 5.22.

Each transformer is connected to the 6-pulse thyristor rectifier, so 5^{th}, 7^{th}, 11^{th}, 13^{th}… etc harmonics are founded in the branch current. These harmonics have 21%, 7.7% 4.6% 3.6%....etc of the value at the fundamental frequency respectively as shown in figure 5.23. These harmonics correspond to the relation of $(kp\pm1)^{th}$ in the converter configuration where **p** is the number of the thyristors and **k** is an integer 1,2,3….etc.

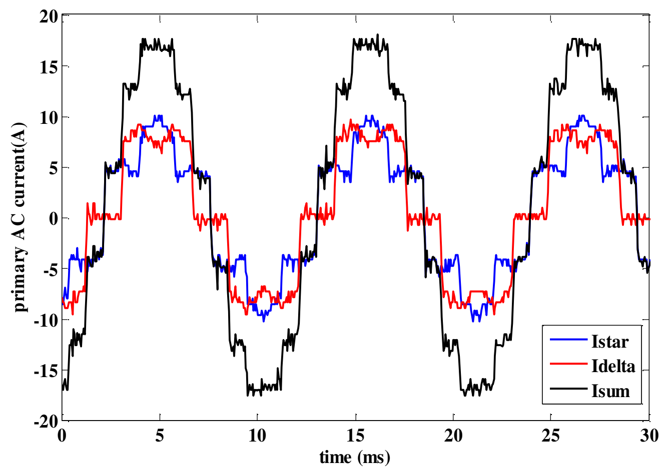

Figure 5.22: AC current in primary of the rectifier transformer at DC output current of 2 kA.

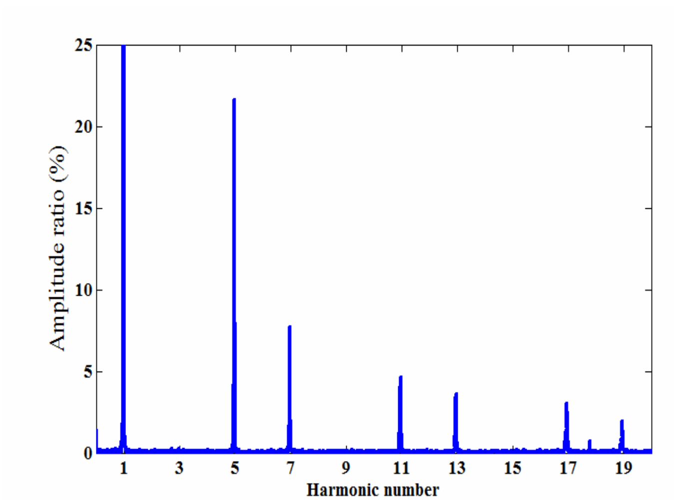

Figure 5.23: Primary AC current harmonics in delta-branch at DC output current of 2 kA.

With the summation of the current in both branches, the 11th, 13th, 23rd, 25th ...etc harmonics are founded with lower values.

These harmonics have 4.66%, 3.4% 1.7% and 1.5% of the value at the fundamental frequency respectively as shown in figure 5.24. This current corresponds to the total AC current for the 12-pulse thyristor.

Therefore, the 12-pulse thyristor has fewer harmonics than the 6-pulse thyristor and it eliminates the harmonics of the order 5th, 7th, 17th, 19th …etc.

At the output current of 4 kA, these harmonics are lower than 2 kA case as shown in figure 5.26 and 5.27.

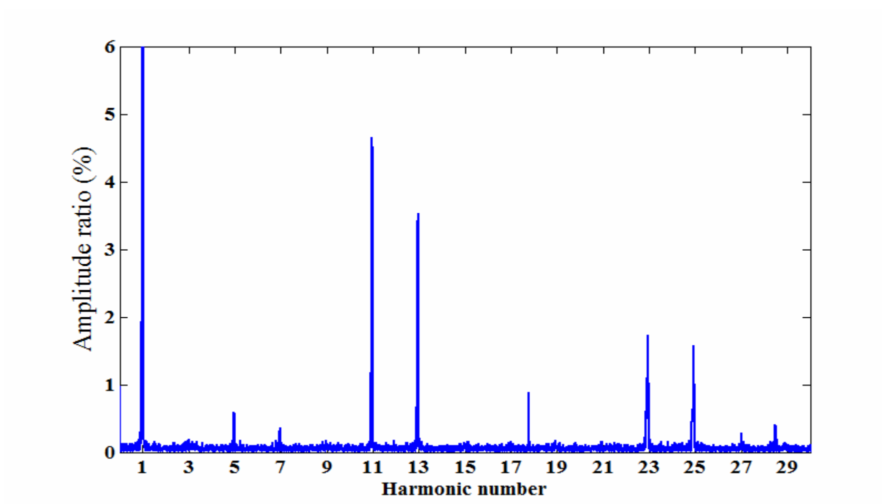

Figure 5.24: Total primary AC current harmonics at DC output current of 2 kA.

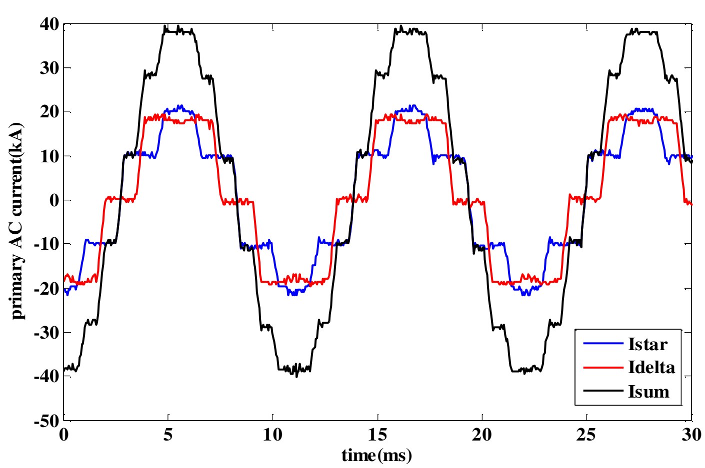

Figure 5.25: AC currents in primary of the rectifier transformer at DC output current of 4 kA.

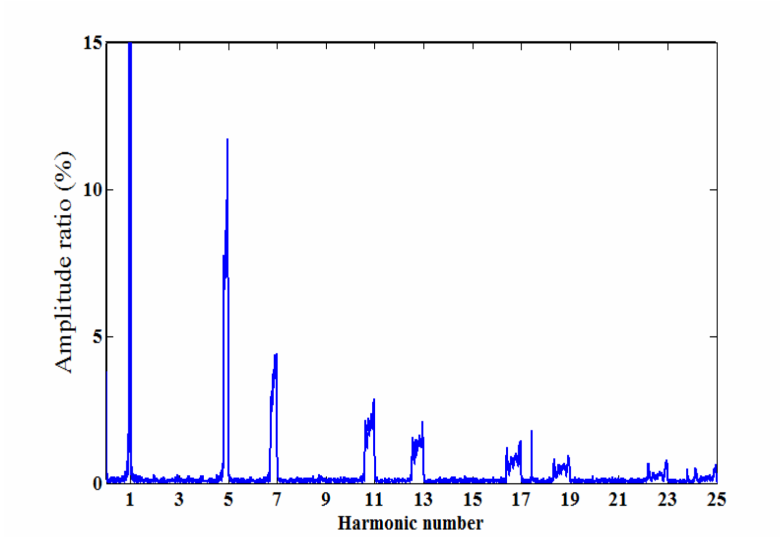

Figure 5.26: AC current harmonics in delta branch at DC output current of 4 kA.

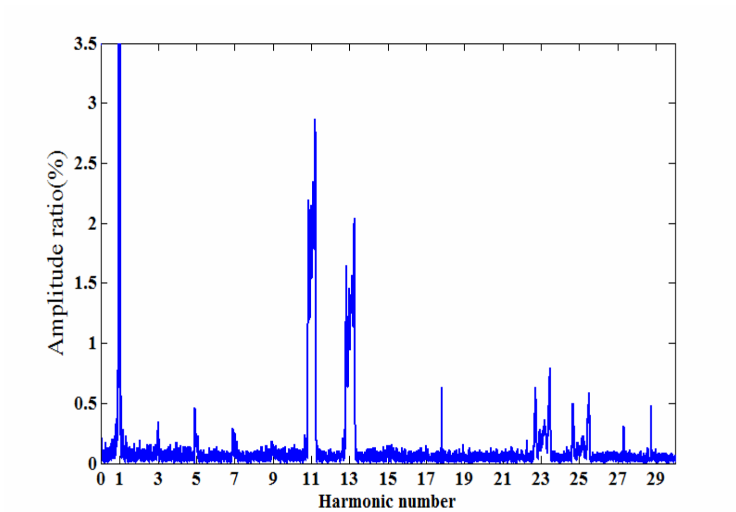

Figure 5.24: Total primary AC current harmonics at DC output current of 4 kA.

Finally, the DC current was measured by ZCT at an output current of 2 kA and 4 kA. As shown in figure 5.28 and 5.30, the real DC current follows the reference current value with a low difference in the case of 2 kA and very low difference in the case of 4 kA.

12-pulse configuration has DC current harmonics of the order 12^{th}, 24^{th},…..etc. Therefore, at an output current of 2 kA, the real DC current has harmonics as 0.14% and 0.022% of the DC value at the 12^{th} and 24^{th} harmonics respectively as shown in figure 5.29.

While at output current of 4 kA, these harmonics are 0.032% and 0.018% of the DC value at the 12^{th} and 24^{th} harmonics respectively as shown in figure 5.31. So the ripples in the DC current are about ± 4 A in the case of 2 kA and are about ± 2 A in the case of 4 kA.

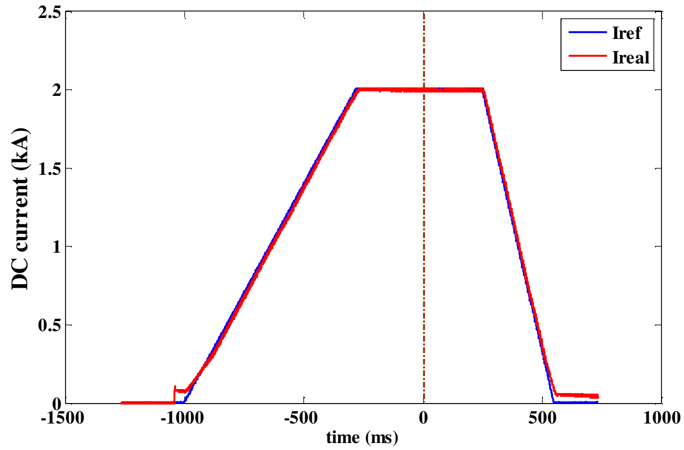

Figure 5.28: the real and reference currents at DC output current of 2 kA.

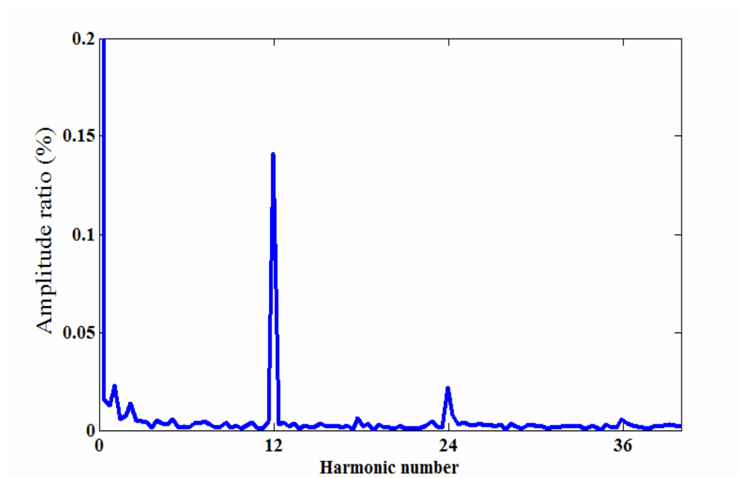

Figure 5.29: DC current harmonics at DC output current of 2 kA.

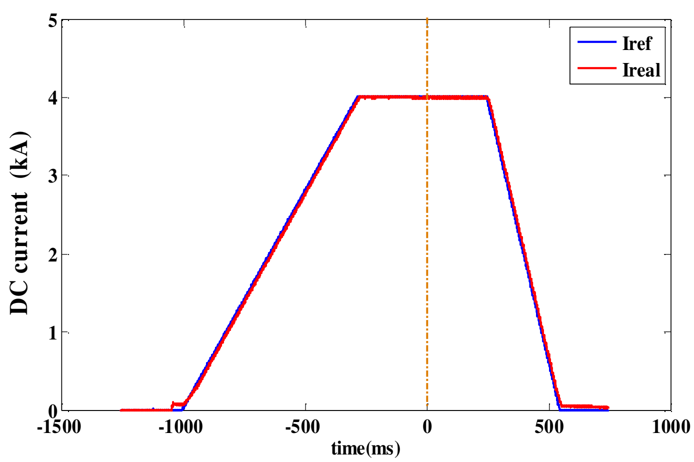

Figure 5.30: the real and reference currents at DC output current of 4 kA.

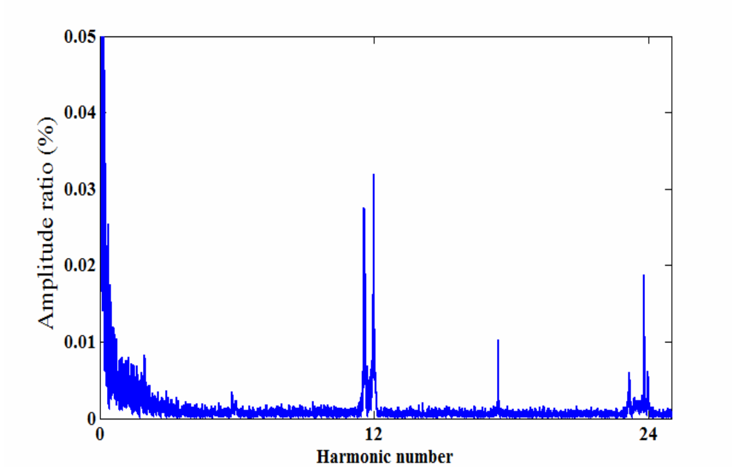

Figure 5.31: DC currents harmonics at DC output current of 4 kA.

Chapter 6

Summary and conclusion

The tests were done to insure that the 12-pulse signals which are transmitted from the current controller (DSP) arrive to each of the 12 thyristor gates via four interface boards.

Firstly, these signals are transmitted via electrical/optical converter to convert them to light signals through interface type A (located in the rectifiers control room).

Secondly, the optical signals are received at interface type B (located in the power rectifiers room) and are converted to electrical signals. Thirdly, the signals are amplified from low voltage to a 40 V signals through interface type C.

Finally, the signals are isolated through an isolation transformer which isolates the control unit (low power side) from the 12-pulse thyristors (high power side) via interface type D.

The tests were done to check these four boards, the optical fibre cables and the proper working of the thyristors.

After checking all the above mentioned, additional tests were done to insure that the levels of the noise on the current and voltage measurements were under acceptable levels.

Once all the converter components were successfully tested, a new group of power tests were carried out connecting the Radial field converter to a dummy load. This load has a similar impedance than the Radial Field coil,. The DC current measured through this load followed the reference current provided by the general control system.

Finally, the same power tests were repeated connecting the RF converter to TJ-II RF coil with correct results.

From the results and discussions presented in this thesis, the following conclusions are drawn:

The 12-pulse rectifier configuration has many advantages: it is a well known technology that achieves reduced levels of harmonics not only on the DC side but also on the supply (AC) side. The 12-pulse parallel configuration provides higher currents than 6-pulse configuration.

- The DC current has low ripple when its value is close to the nominal due to the reduced value of the firing angle.
- The ripple of the DC voltage is proportional to the ripple of the DC current, i.e. when the ripple of the current is decreased; the ripple of the voltage is decreased too.
- The 12 pulse configuration provides harmonics in the source of the order 11^{th}, 13^{th}, 23^{rd} ,24^{th} …etc and eliminate the harmonics of the order 5^{th}, 7^{th} , 17^{th}, 19^{th} …etc i.e., it is provided harmonics of the order $12\,k \pm 1$ where k is an integer.

- When several similar converters, with controlled rectifiers, are connected to the same busbar, some cancellation of harmonic currents takes place due to phase shifts between the firing angles of converters running at different speeds.
- In the dummy load measurements; the difference between the real and reference-currents is due to the parameters of the current controller are not adjusted precisely for the dummy load.
- The voltage profile is similar to the current profile because the load is more resistive.

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Declaration

I herewith declare in lieu of an oath that I have produced the aforementioned thesis independently and without using any other than the aids listed.

Any thoughts directly or indirectly taken from somebody else's sources are made discernible as such.

To date, the thesis has not been submitted to any other board of examiners in the same or a similar format and has not been published yet.

Madrid

July, 2009 Kamal Ahmed