Design and development of high voltage regulated power converters based on advanced techniques with suitable protection schemes and study on EMI characterization

By

SAJJAN KUMAR THAKUR
(Enrollment No: ENGG04201104003)

Variable Energy Cyclotron Centre
Kolkata-700064, India

A thesis submitted to the
Board of Studies in **Engineering Sciences**
in partial fulfillment of requirements
for the Degree of

DOCTOR OF PHILOSOPHY

of

HOMI BHABHA NATIONAL INSTITUTE

June, 2018

Homi Bhabha National Institute

Recommendations of the Viva Voce Committee

As members of the Viva Voce Committee, we certify that we have read the dissertation prepared by Sajjan Kumar Thakur entitled "Design and development of high voltage regulated power converters based on advanced techniques with suitable protection schemes and study on EMI characterization" and recommend that it may be accepted as fulfilling the thesis requirement for the award of Degree of Doctor of Philosophy.

D. K. Srivastav 8/04/2019

Chairman – Dr. D. K. Srivastava Date:

Guide / Convener - Dr. Alok Chakrabarti Date:

Alok Chakrabarti 08-04-2019

Examiner - Prof. N. K. Kishore Date: 8/4/19

Member 1- Dr. V. S. Pandit Date: 8/4/2019

Member 2- Dr. Sandip Sarkar Date: 08/04/19

Sandip Sarkar

Technology Adviser – Dr. Sumit Som Date: 08/04/19

08/04/19

Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to HBNI."

I/We hereby certify that I/we have read this thesis prepared under my/our direction and recommend that it may be accepted as fulfilling the thesis requirement.

Date: 8/4/2019

Place: VECC

Alok Chakrabarti

Guide

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at Homi Bhabha National Institute (HBNI) and is deposited in the Library to be made available to borrowers under rules of the HBNI.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the Competent Authority of HBNI when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SAJJAN KUMAR THAKUR

DECLARATION

I, hereby declare that the investigation presented in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree / diploma at this or any other Institution / University.

SAJJAN KUMAR THAKUR

List of Publications arising from the thesis

Journal Publications:-

1. **S. K. Thakur**, "Design and performance of high voltage power supply with crowbar protection for 3-Φ high power rf amplifier system of cyclotron". Journal of Instrumentation (JINST 11 T07004), vol.-11, 2016.
2. **S. K. Thakur**, S. Kumari, Yashwant Kumar, "Design and performance analysis of a crowbar-less high voltage power supply based on PSM technique" Sadhana Journal, vol-43, issue- 8, 2018, pp 1-9/129: 129.
   https://www.ias.ac.in/article/fulltext/sadh/043/08/0129.
3. **S. K. Thakur**, Y. Kumar, "Design development and testing of high voltage power supply with crowbar protection for IOT based RF amplifier system in VECC". Journal of Instrumentation (JINST 13 T05009), vol. –13, 2018.

Conference Publications:

1) **S. K. Thakur**, Santwana K. , A. De, Y. Kumar, V. Lilhare, A. Bera, S. S. Pal, V. K. Khare, T. P. Tiwari, S. Saha. "Design and Development of Prototype High Voltage Power Supply with PSM Technique for RF Amplifier". InPAC-2013, Kolkata, 2013, pp 570-572.
2) S. Srivastava, Yashwant Kumar, A. Misra, **S.K. Thakur** and V.S. Pandit. "Optimum Design of Buck Converter Controller using LQR Approach". IEEE International Conference in Advance computing- 2013.

3) Yashwant Kumar, S. Srivstava, A. Bera, T.P. Tiwari, H.K. Panday, **S.K. Thakur**, S. Saha. “Design and development of switch mode power supply for 3.0 kW a Solid State RF amplifier”, InPAC-2015, Mumbai.

Other Publications :

1) De A.; Kumari S.; Khare V.K.; Pal S.S.; Sadhukhan A.; Meshram V.K.; **Thakur S.K**.; Saha S. “Design Analysis and Implementation of a Dynamic Voltage Restorer “, Journal of Low Power Electronics (JOLPE), Vol 9, No. 3, 2013, pp-340-349.
2) Saurabh Srivastava, Anuraag Misra, **S. K. Thakur**, V. S. Pandit, “An optimal PID controller via LQR for standard second order plus time delay systems”, ISA Transactions, 60.(2016) 244-253.
3) V. S. Pandit, G. Pal, **S. K. Thakur**, P. Singh Babu, A. Goswami, Mou Chatterjee, R.C.Yadav, S. Srivastava, S. Bhattacharya, S. Roy, C. Nandi, A Misra. “Microwave ion source and injection system for a high current compact cyclotron”, 2nd International Workshop on ADS & Thorium Utilization, December 11-14, 2011, BARC Mumbai.
4) Anirban De, S.S. Pal, P. Bhaskar, S. Kumari, V.K. Khare, A. Duttaroy, M. Garai, **S.K. Thakur,** S. Saha, Sankha Chattopadhyay, Luna Barua, Sujata Saha Das, U. Kumar, M.K. Das. “An Embedded System based Computer Controlled Process Automation for Recovery and Purification of 99mTc from (n,γ) 99Mo”, Proceeding of the 9th International Workshop on Personal Computers and Particle Accelerator Controls (PCaPAC2012), VECC, Kolkata, pp. 211-213, 4-7 Dec. 2012.
5) De A.; Kumari S.; Khare V.K.; Pal S.S.; Sadhukhan A.; Meshram V.K.; **Thakur S.K**.; Saha S. “Design, Development and Testing of a DSP Based Dynamic Voltage

Restorer", Published in Electronic System Design (ISED), 2012 International Symposium, pp.157-161, 19-22 Dec. 2012.

6) Bidhan Chandra Mandal, Uttam Bhunia, Javed Akhtar, Jedidiah Pradhan, Chinmay Nandi, **Sajjan Kumar Thakur**, Manoranjan Das, Gautam Pal and Subimal Saha. "Dynamic loss analysis for 4.5 MJ SMES", Paper Presented in National Symposium on Cryogenics (NSC-24) held during January, 2013 at IPR, Ahmedabad.

7) V.S. Pandit, P.Sing. Babu, A. Goswami, S. Srivasatava , A.Misra , Mou chatterjee, P.Y.Nabhiraj, R.C.Yadav, S.Bhattacharya, S.Roy, C.Nandi, G.Pal, **S.K.Thakur**, "Development of microwave ion source and low energy beam transport system for high current compact cyclotron", Paper presented in International conference on electromagnetic isotope separators and related technologies (EMIS-2012), Matsue, Japan.

8) H.K.Pandey, T. K. Mandi, Y. Kumar, D.P. Dutta, S. Basak, **S.K. Thakur**, K.P.Ray, A. Bandopadhyay. "Design and development of 37.8 MHz, 2.0 kW RF amplifier for re buncher of RIB project". Paper published in InPAC-2013 held at VECC, Kolkata , 2013, pp-624-626.

9) Yashwant kumar, Santwana Kumari, M. K. Ghosh, A. Bera, A. Sadhukhan, S. S. Pal, V. K. Khare, T. P. Tiwari, S. K. Thakur, S. Saha. "Design and Development of Power Supplies for High Power IOT based RF Amplifier". Paper published in InPAC-2013 held at VECC, Kolkata, 2013, pp. 500-502.

10) Saurabh Srivastava, Yashwant Kumar, Anuraag Misra, Vijay Shanker Pandit, Sajjan Kumar Thakur. "A Control Strategy for Highly Regulated Magnet Power Supplies Using a LQR Approach" Paper presented in ICALEPCS -2013.

11) J Pradhan, Nisith Kr Das, Anindya Roy, Uttam Bhunia,Vipendra Khare, **Sajjan Kumar Thakur** and S. Saha. “Design and Development of Cryogen Free Cryogenic Test set-up”. 26th International Cryogenic Engineering & International Cryogenic Material Conference (ICEC26-ICMC-16), New Delhi, 2016.

12) U Bhunia, J Pradhan, A Roy, V K Khare, M K Dey, **S K Thakur**, H Kanithi. “Transient stability of NbTi Rutherford cables for energy storage magnet applications”. 26th International Cryogenic Engineering & International Cryogenic Material Conference (ICEC26-ICMC-16), New Delhi, 2016.

13) V. K. Khare, U. Bhunia, A. De, J. Pradhan, **S. K. Thakur**, M. Das, S. Saha. “Joint development and testing of Rutherford NbTi cable for SMES coil”. 26th International Cryogenic Engineering & International Cryogenic Material Conference (ICEC26-ICMC-16), New Delhi, 2016.

14) Md. Zamal Abdul Naser, Siddhartha Dechoudhury, Manas Mondal, A. Polley, H.K. Pandey, D.P. Dutta, **S.K. Thakur**, Arup Bandyopadhyay, Vaishali Naik and Alok Chakrabarti. “Present status of design, installation and testing of electron gun and low energy beam transport line of electron linac at VECC”. InPAC-2015, held during December 21-24, 2015 in Mumbai.

SAJJAN KUMAR THAKUR

Dedicated to my parents

Shri K. N. Thakur and Smt. Mira Thakur.

ACKNOWLEDGEMENTS

I express my sincere gratitude to my guide Dr. Alok Chakrabarti for the valuable guidance and encouragement to my PhD works. I am greatly indebted and respectful to Dr. V. S. Pandit for his guidance and continuous encouragement throughout my thesis work, without whose support, my thesis could not have been possible to come to the concluding stage. I would like to express my heartfelt thanks to Dr. D. K. Srivastava, Former-Director, VECC and Chairman of my PhD committee for his kind support and encouragement. I take the opportunity to thank Dr. Sumit Som, Head, ATG for the technical guidance and encouragement throughout the work during development and testing of the High Voltage power supplies with RF systems.

I express my sincere gratitude to Dr. R. K. Bhandari, Former-Director, VECC who has granted me the permission to carry out my PhD work in the field of High Voltage. I take this opportunity to thank Shri Subimal Saha, Ex-Head, Accelerator Technology Group for providing me the opportunity to work on high voltage power systems for RF Amplifiers for the cyclotrons. I would like to thank my PhD committee members Dr. Sandip Sarkar, SINP for his valuable suggestions and encouragements. I am sincerely thankful to Dr. Paramita Mukherjee, former Dean, HBNI, Kolkata for her continuous supports, encouragements and valuable suggestions throughout my PhD work.

I would like to express my sincere thanks to each and every staff members of PE&MCD section for their technical supports all the time during the development and testing of high voltage power systems which are very dangerous and critical in nature. My sincere thanks to my colleagues Shri Saurabh Srivastava, Shri Yashwant Kumar, Smt. Santwana Kumari, Dr. Anuraag Misra, Dr. Anirban De, Shri T P Tiwari, Shri J. S. Prasad, Shri SS Pal and each and everybody from PE&MCD section and RF Section for their continuous supports without which it would not be so easy to achieve the goal.

I am very much thankful to my wife Lina for her consistent motivation, encouragement, support and self-sacrifice during my PhD work. I am thankful to my son Rohan for keeping my mind refreshed by enjoying the precious days of his childhood with him. I am eternally grateful to my parents and parents-in-law for everything what they have done for me in my life. Above all, I owe it all to Almighty God for granting me the wisdom, health and strength to undertake this research task and enabling me to its completion.

SAJJAN KUMAR THAKUR

Table of Contents

Synopsis

The work presented in the thesis deals with the development of a number of high voltage power converters / supplies, viz. 20 kV, 22.5 A; -30 kV, 3.2 A; -40 kV; 5 A for the *K* 500 Superconducting Cyclotron and other project at VECC, Kolkata. In the present dissertation, several topologies, e.g., switching type, high voltage tetrode tube based linear regulator type, primary phase angle controlled by using SCRs were studied for the development of high voltage power converters for the cyclotrons at VECC. Subsequently, their design and development was carried out and then the converters were coupled to the cyclotrons at VECC. Their performances have been satisfactory even after 6 years of continuous operation. The performances of the conventional power supplies are required to be improved as demanded from load end which is carried out by adopting PSM topology as being a latest and emerging technique. Generally, the conventional power converters are larger in size and contain high stored energy. Hence, rf tubes need to be protected against excessive energy dissipation during internal arc fault for which a crowbar protection system is required to be implemented. However, in PSM based high voltage power converters, no additional device is necessary for the crowbar protection. This is because the PSM technique uses high frequency switching in each power module which requires very low capacitors and results in very small stored energy. A Digital Signal Processor (DSP) based controller is developed indigenously which has less susceptibility to environmental noise that results better regulation, stability and control.

The design and development of these high voltage power supplies (HVPS) require lots of efforts for (i) finalizing the appropriate topologies to meet the requirements, (ii) design of appropriate control architecture, (iii) design of HVPS based on available components including interlocks and protection system and finally (iv) completely new development of a HVPS of rating -40 kV, 5 A using PSM technique which would allow us to meet the design goals in a much more efficient and safe way. It may be mentioned that many of these converters could have been commercially procured but the prohibitive cost, the long term maintenance issues and minimizing of machine down time are the factors that have led to the decision to develop the new technology. In absence of enough detailed literatures on these converters, the developments become an intensive R&D which involves detailed study, work out of the design, prototype fabrication before finalizing the actual unit of power supply and finally the development, testing and commissioning of the high voltage power supply. Further, we believe that these developments have certain unique aspects that are novel in the sense those were done differently in the commercially available converters.

The present thesis consists of six chapters whose main contents are described below.

Chapter-1 is the introduction that contains discussion on various aspects of the high voltage regulated power supplies along with their control. The needs for the improvements as demanded by the various applications are worked out which created the motivation for the present research work. A part of the chapter is also dedicated to literature survey that brings out the present state of the art development in this field.

Chapter-2 contains the detailed description of design, fabrication and testing of a high voltage power supply rated at 20 kV, 22.5 A (output power 450 kW) along with ultrafast crowbar protection system. The Radio Frequency system of *K* 500 Superconducting Cyclotron (SCC) at VECC consists of 3 nos. of rf cavities (dee) separated at 120^o apart in the median plane. Each cavity is designed for 80 kW rf power to produce dee voltage of 100 kV in the operating frequency range of 9-27 MHz. To produce such a high voltage, each cavity requires individual tetrode tube (Eimac 4CW150,000E) based rf amplifier.

The power supply rated at 20 kV, 22.5 A has been being used to feed power to the anodes of all three tetrode tubes based rf amplifiers for K 500 superconducting cyclotron (SCC) at VECC campus. All the three tetrode tubes are protected by a single ignitron based crowbar protection system against internal arcing fault in any of the tubes. The tubes are very much prone to undergo internal arcing and energy deposition in the tube during internal arcing must be restricted to the value specified by the manufacturers. In order to minimize the deposition of energy, a very specialized technique is adopted that diverts the energy through an ignitron followed by tripping the input power. A technique has been designed for fast sensing of the arc current and initiating the triggering of a high voltage ignitron within 5 μs in order to limit the energy deposition which is called crowbar protection. The wire burn test was performed for confirmatory test of the crowbar protection system, a special technique to simulate the actual deposition of stored energy. This chapter presents the salient design features, simulation, in-house development and technical challenges during the testing of the high voltage anode power supply and crowbar protection system for the rf amplifier tubes.

Each tetrode tube requires individual dc power supplies for biasing its electrodes: anode, screen, grid and filament with respect to grounded cathode. All these power supplies are designed, fabricated and tested along with Local & Remote controls, ON/OFF sequencing together with the interlocks & protection. The ratings of the power supplies are: filament power supply 16 V, 220 A, grid power supply -500 V, 0.1 A with 100 ppm stability, screen power supply 1600 V, 500 mA with 60 ppm stability and a high voltage anode power supply rated at 20 kV, 22 A for the anodes of three tubes.

In **Chapter 3**, the development of a negative polarity high voltage power supply (-30 kV, 3.2 A) required for biasing the electrodes of Inductive output tube (IOT) based rf amplifier test stand working at 700 MHz in continuous mode has been presented.

The development of multi-cell (5 cell) medium-β Superconducting rf linac cavity has been taken up at Variable Energy Cyclotron Centre (VECC), Kolkata, as a part of Indian Institutes - Fermi Lab, USA collaboration. For this the design and development of a high power (~60 kW at 700 MHz in CW mode) rf amplifier has been taken up based on Inductive Output Tube (IOT). For this, a set of dc power supplies for biasing the IOT has been developed, installed and tested.

High voltage power supply (HVPS) of rating -30 kV, 3.2 A is designed and developed for biasing IOT Cathode. A back to back primary SCR based phase angle controlled topology is utilised for voltage regulation. The crowbar protection system is implemented which is more complex in negative polarity power converter. The complicacy in implementing the crowbar protection by using ignitron (NL7703) is also addressed with the solution. Testing of the crowbar system is done by using wire burn method. Other auxiliary power supplies are used for grid, filament, ion pump, focus coil. The power supplies for grid, filament and ion pump of IOT are with respect to the cathode which is floating at high voltage. So, these power supplies are placed at a high voltage deck and parameters control and monitoring are done through a PLC based system. A high voltage deck is specially designed by using insulating material with metallic enclosure having isolation ~40 kV to house these power supplies. The electrical power is fed through an Isolation Transformer of isolation 40 kV. These power supplies are controlled by a PLC, which communicates through an Optical Fibre link to the PC.

Chapter 4 is dedicated mainly to the development of a high voltage power supply based on state of the art pulse step modulation (PSM) technique for ~60 kW continuous wave (cw) rf amplifier based on Inductive output tube (IOT) TH793-1 operating at 700 MHz. For a nominal beam bias, cathode requires a high voltage power supply (HVPS) of rating -40 kV, 5 A is considered for design and development. The present development is aimed to utilise a modern technique meeting all the important criteria, i.e., solid state based modular construction, small size, crowbar-less design, reliable operation, voltage regulation with higher efficiency, fast response and most importantly easy servicing. In this chapter, the design details and test results of high voltage power supply (HVPS) by using DSP TMS320F28335 as the main controller has been presented.

Inductive output tube (IOT), a hybrid of klystron and triode, has advantages in term of better linearity and efficiency over klystron and in terms of gain over tetrode tube. IOT requires several power supplies for biasing its electrodes. High voltage power supply for cathode is one of the important which should have voltage regulation better than 0.5% and low ripple. The high voltage power converter (rating -40 kV, 5 A) is designed and developed by using Pulse Switch Modulation (PSM) topology, a latest technique required to fulfil most of the designed features. PSM based high voltage power supply consists of several switched type power modules (SPMs) and the output voltage is obtained by adding the output voltages of each SPMs in series and modulating their pulse widths and phase delay time. This results into very low ripple voltage at higher frequency which ultimately requires very small filter capacitor resulting into very low stored energy. Thus PSM based power supply does not require a separate crowbar protection system.

The high voltage power supply (HVPS) consists of 60 switched power modules (SPMs) and two resin cast air cooled multi-secondary transformers, each having 30 secondaries star-connected, 3-phase, line voltage 580 V, 50 Hz to power each SPM individually. The primary connection of one transformer is delta and other is star for providing 12 pulse rectification features when both transformers power equal SPMs. Solid state based SPM uses an IGBT in series as a buck converter with a typical output voltage of around 780 V at a fixed duty cycle of 80% at switching frequency 5 kHz. The operation involves switching-on the required number of SPMs till a set value of output voltage is arrived. The output voltage finer setting and regulation is accomplished by pulse width modulation (PWM) of 2 SPMs with variable dc voltage. A DSP based control system is developed in order to ensure the trouble free operation of the power supply as well as option for future upgrade without much change in hardware.

For biasing an IOT, auxiliary power supplies for filament, grid and ion-pump are needed with respect to cathode which are kept at high voltage deck at 50 kV isolation and powered by a resin cast isolation transformer of isolation voltage ~50 kV. Two Ethernet optical fibre media converters connected to a PLC through 5 m long optical fibre link for their controls and communications. Focus coil power supply is with respect to the ground level so, it is easy to control.

Chapter 5 describes the study on harmonics and EMI, their basic concepts of generation and side effects. Electromagnetic interference (EMI) becomes a major concern for high power SMPS power supplies and various types of motor drives in electrical field.

It causes conducted and radiated EMI noise which creates nuisance for other electronic equipment. Electromagnetic compatibility (EMC) is the ability of any electronics systems to function without causing or experiencing performance degradation due to EMI produced nearby.

Chapter 6 contains the conclusions and perspective of high voltage related work to be carried out at VECC in future.

List of Figures

List of Tables

List of Abbreviations

SMPS	Switching Mode Power Supply
PWM	Pulse Width Modulation
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
PD	Proportional Derivative
PFC	Power Factor Correction
PI	Proportional Integral
PID	Proportional Integral Derivative
DCCT	Direct Current, Current Transformer
IC	Integrated Circuit
IGBT	Insulated Gate Bipolar Transistor
EMI	Electromagnetic Interference
rf	Radio Frequency
PS	Power Supply
PSM	Pulse Switch Modulation
SPM	Switched Power Module
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
ECR	Electron Cyclotron Resonance
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching
IOT	Inductive Output Tube

IGBT	Insulated Gate Bipolar Transistor
ESP	Electrostatic Precipitator
ADS	Accelerator Driven Systems
RIB	Radioactive Ion Beam
LCW	Low Conductivity Water
HVPS	High Voltage Power Supply
VECC	Variable Energy Cyclotron Centre

CHAPTER 1

Introduction

1.1 Background

High voltage dc power converter (supply) is one of the key components for electrostatics applications extensively used in the field of Accelerators, defense, consumer markets and various industries. Industrial processes, for example, require significant performances and operational conditions to enhance the productivity and to improve the quality at reduced cost which prompted for further advancements with improved features. In accelerators, the high voltage power supplies (HVPS) at high power are required for various tubes i.e. Klystron, Tetrode tube, Inductive output Tube (IOT) based rf amplifiers. These are primarily used to produce high electric field at radio frequency that is synchronized with the speed of beam. Some other major applications of high voltage power supplies involve capacitor charging, missile firing, fabric industries, ESP and many other industrial applications.

The Variable Energy Cyclotron Centre at Kolkata is a premier institute for nuclear science having excellent infrastructure for advanced research and development in accelerator technology. Room temperature K 130 cyclotron was first indigenously developed in India during 1977 and since then variety of activities have come up, such as, extraction of heavy ion beam with external ECR, Medical Cyclotron, radioactive ion beam (RIB) facility and many other activities related to material science ADS, detector etc. Radioactive Beams (RIB) are indispensible tools for nuclear science to study structure of unstable nuclie. Several components of RIB facility have already been tested and installed. VECC is setting up a medical cyclotron to produce proton beam with energy up to 30 MeV and current up to 350 μA to produce various isotopes for medical applications. The cyclotron will also be used for R&D in material science and to settle the various problems related with handling of high beam current on ADS related components. Apart from that, VECC is also involved in the studies on using cyclotrons to achieve high power proton beam, development of high current at low energy part of the accelerator to settle various space charge related problems and R&D on superconducting cavities. With the vast experience and expertise in accelerator technology, the challenging tasks of constructing superconducting (SC) cyclotron and their different systems have been executed. This cyclotron has already delivered internal beam and some modifications are underway to achieve external beam. The SC cyclotron consists of assembly of various subsystems such as cryogenics systems, magnets, rf system, ion source, injection and extraction system, vacuum, control systems, beam transport, data processing systems etc. For the rf systems, high power and high voltage power supplies are needed for producing high electric field at very high frequency.

The power supplies are the major components for any sub-systems of accelerators, i.e., rf system, main magnet, various other beam-line magnets and ECR. Performance and beam quality of any accelerator depends on the quality of the power supplies. As the advancement in the technology is going on, more and more accelerators are coming up and accordingly the demand of high voltage power supplies with improved performance have been also increased. Considering the high demands of custom built high voltage power supplies, it was very important for in-house development so that any further improvement in future can be easy to incorporate.

For high voltage dc power converter, switching technique is adopted mainly for improved efficiency, faster response and good power management [1]. But on the other hand, it produces noise which is very much vulnerable for most of the applications. Switching at higher current produces more EMI and noise level and thus at much higher power, the noise level could be a very serious issue. In order to minimize the noise level, soft switching technique can be applied [2, 3]. But it has some limitations which may not be very useful for a power supply of higher power. For very high power at high voltage, Pulse-Step Modulation technique (PSM) can be adopted utilizing the switched type modules. In this scheme, there are several modules of small power rating which are switched at some fixed time delay between one to another and finally their output voltages are connected in series to attain requisite voltage. A part of the work reported in the thesis is on the design and development of a high voltage power supply rated at -40 kV, 5 A based on PSM topology.

1.2 Power converter topologies: switching and PSM

Transformation of dc voltage from one level to other level is accomplished by a dc-dc converter. There are various schemes of dc-dc converters which involve the combination of power components along with control electronics for regulations and protections. Linear type power converter has very specific range of applications due to its inherent limitations in efficiency due to higher dissipation and non-availability of high voltage components. On the other side, switching type converter topologies are widely used in the dc power converters in various schemes [1] because of its inherent advantages and faster response. The switch-mode operation results in low power dissipation as it operates either in switch-on or switch-off mode. Due to switching at high frequency, the filter capacitor requirements are greatly reduced which makes it very compact and efficient. Each module is a buck type switching regulator used in PSM based high voltage power supply.

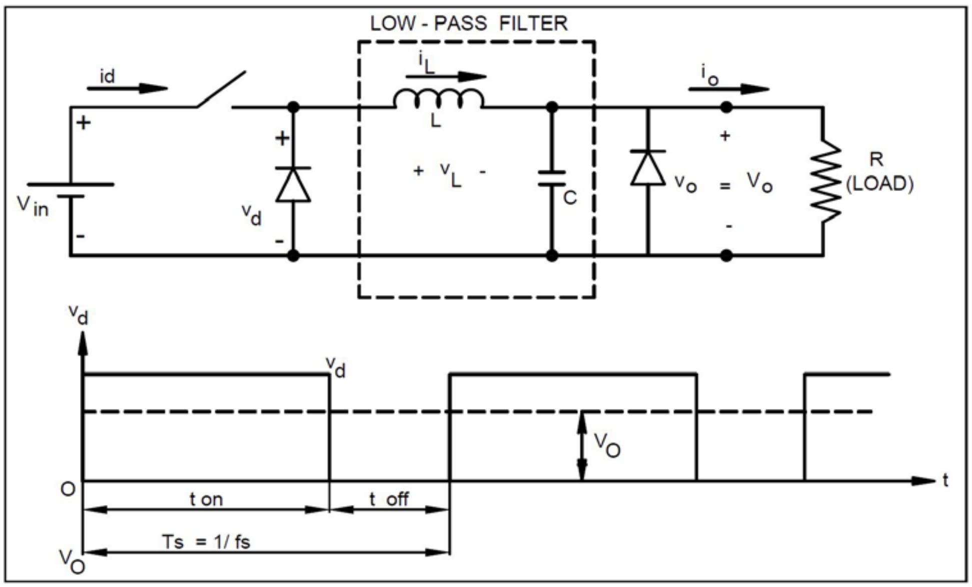


Figure 1-1: Schematic diagram of buck type switching regulator

The configuration of buck type switching regulator is shown in **Figure 1-1** where IGBT is used as a regulating element and regulation is achieved by varying the duty cycle. In this configuration, the output voltage is directly proportional to the duty cycle [1, 4].

$$V_0 = \frac{1}{T_s}\left[\int_0^{t_{on}} V_d\,dt + \int_{t_{on}}^{t_s} 0\,dt\right] = \frac{t_{on}}{T_s} V_d = DV_d$$

Where V_o denotes output voltage, D duty cycle and V_d is Input dc voltage. However, these benefits of switching power supplies come at the cost of higher complexity and electromagnetic interference (EMI) and switching losses. Further, due to high-frequency switching, the size of the isolation transformer and passive components in the filter are drastically reduced. Fast response, smaller size and lower cost are the other important features of switching power supplies.

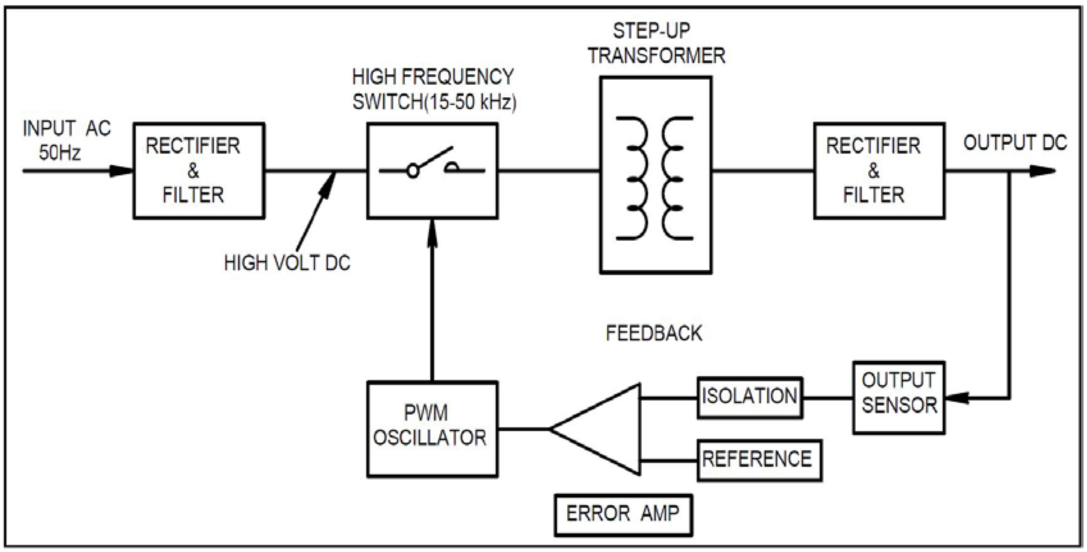


Figure 1-2: Block diagram of a switching type dc-dc power converter.

There are various other configurations of Switching regulators, i.e. Boost converter, Forward converter, Push-Pull type, half bridge, full bridge etc. In some configurations, a high frequency transformer is used to step-up or step-down the voltage. A block diagram of a typical switching type dc-dc regulated power converter is shown in **Figure 1-2**. Increase in switching frequency will increase the noise as well as switching loss. These shortcomings can be minimized by implementing soft switching technique. Soft switching normally uses a resonant circuit consisting of L-C which is tuned to operate at certain frequency matching with the switching frequency.

Hard switching at higher voltage or current will contribute more switching loss and EMI generation. In soft switching, either voltage or current in the switching elements are made zero at the time of switching transitions which automatically reduces the switching loss as well as noise generation considerably [2-4]. It may be accomplished in two ways- Zero-voltage-switching (ZVS) and Zero-current-switching (ZCS) which collectively is called soft switching. In ZVS, switching takes place when the voltage across it is zero and in ZCS, switch occurs when current through it is zero [3].

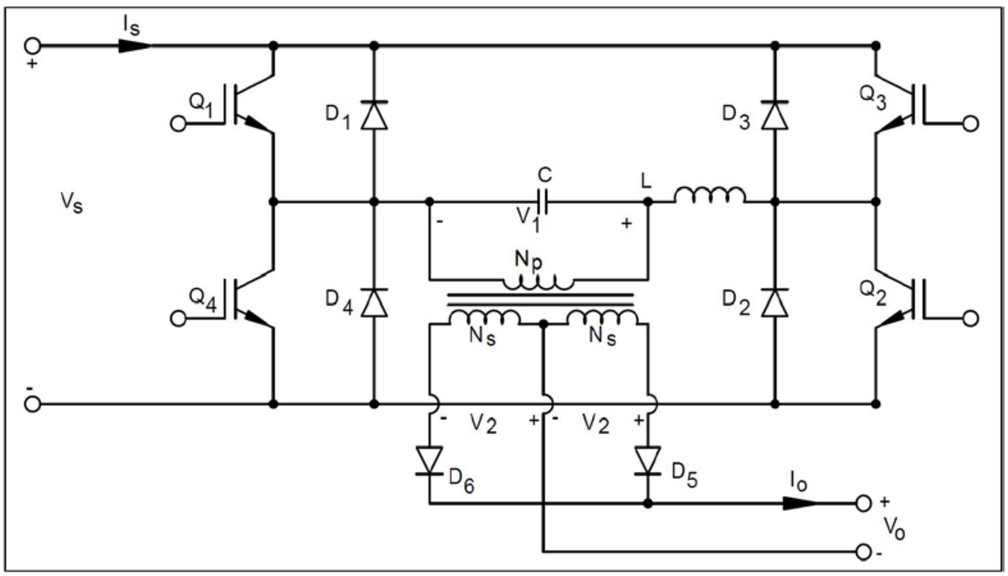


Figure 1-3 : dc-dc power converter with soft switching scheme

There are several schemes for soft switching and a typical soft switching type dc-dc converter is shown in **Figure 1-3**. In this, the resonant frequency of combination of L and C is matched with the switching frequency. In switching type dc-dc power converters, passive turn-on and passive turn-off snubers are used to damp the rate of rise of voltage and current and clamps the overshoots during switching transitions. It helps in reduction of the switching loss in the components as well as noise.

In order to utilize the advantages of switching regulators for a high power and high voltage power converters, Pulse-Step Modulation (PSM) topology is adopted utilizing state of the art technique. Multiple switching modules based on buck type converters are used with phase shifted switching pulses which make the PSM based high voltage power supply a modular and compact. Due to high frequency switching, lesser capacitors are used and thus low stored energy. The modules are switched on one after another at a fixed time delay and any voltage level can be set to the rated voltage can be obtained just by switching on required number of series connected modules.

Each module consists of a series connected IGBT as buck converter and switched at a fixed frequency. The frequency is selected according to the switching characteristic of the IGBTs used in the modules which is trade-off between faster response and smaller filter versus the switching loss. The regulator would be dynamically adjusting the pulse width to control the output voltage. One another IGBT in parallel at output is connected which is used during switch off the module to discharge the stored energy very fast. An L-C (inductor-capacitor) filter is used with a free-wheeling diode at the output. The devices that ultimately apply or control the high voltage to the rf sources must be located as close as reasonably possible to the rf sources to minimize the energy stored in the high voltage cable between the controlling device and the rf source, thereby reducing the energy that could be deposited into the tubes [5, 6] during internal arcing fault condition.

1.3 Research motivation

The growing demand of regulated high voltage power converters for rf amplifier tubes has motivated us to develop an in-house technology which could be used for the development of new high voltage power supplies in future also, as per the requirements. There are some manufacturers in the world scenario who manufactures PSM based high voltage power supply which are very expensive and no technical details available. Also, availability of after sales supports for future maintenance is very poor which may affect the downtime of a system.

Keeping in view the accelerator projects that VEC Centre is going to take up in near future, development of highly efficient high voltage-high power converters is one of the key areas of R&D. For accelerators and in the Radioactive Ion Beam Project at VEC Centre, there will be plenty of requirements of high voltage power supplies. This pledge has motivated us for the design and development of high voltage power supply (HVPS) by using our own control strategy by incorporating PSM technique. To start with, a HVPS rated at -40 kV, 5 A based on PSM topology is chosen to design meeting all the customized features viz. modular design, better regulation, low harmonics, high efficiency, low ripple, low EMI and computer control. This HVPS will later be used to test with IOT based rf amplifier to test a superconducting multi-cell rf cavity.

Feasibility study was done and a prototype of PSM based power supply of smaller rating was designed with simulation using four modules. In order to realize the precise control of modules, a DSP based controller is used as a core controller which controls the switch-on and switch-off of the modules and time interval that can be adjusted from 1μs to few ms. It comprises of two multi secondary transformers with sufficient isolation voltage are used to feed electrical power to the modules. All the modules are kept at high voltage deck and connected through the optical fiber for providing galvanic isolation. During the prototype development, different control strategies were tried and final scheme was established. After complete testing of the prototype, actual high voltage power supply based on PSM of rating -40 kV, 5 A was taken up for design, simulation and development for testing a rf cavity. An important motivation for this work is the development of a new technology related to high voltage system customized as per our requirements with all necessary features.

1.4 Contribution of the thesis

The work presented in the thesis deals with the development of a number of high voltage power converters, viz. 20 kV, 22.5 A; 30 kV, 3 A; -40 kV; 5 A for the *K* 500 Superconducting Cyclotron and other projects at VECC, Kolkata. It includes the design, simulation, development, testing and commissioning for all these HVPS. The power supplies developed fall into two broad categories: (a) those designed and built following conventional techniques, such as switching type, tetrode based, linear regulator type, SCR based phase control, etc, and (b) PSM based technique. The PSM based power supply contains very less stored energy which allows one to design much simpler crowbar protection system as compared to the ones used for conventional type where stored energy is significantly high.

It is obvious that the volume of the work is huge and is impossible to carry out without substantial and able support from others. Indeed, a number of colleagues of researcher (author of this thesis) have contributed in it. However, finalization of topologies, complete design of HVPS along with the protection systems, simulation and components selection have been carried out entirely by the researcher himself. Also, being the team leader and person responsible for building the high voltage converters, the researcher's participation in all the subsequent stages that include development, testing and commissioning, has been intense including overall testing. Furthermore, PSM based high voltage power supply has been developed first time at VECC, Kolkata and no such work has been previously carried out at VECC.

1.5 Outline of the thesis

The organization of thesis is as follows: At first the introduction and motivation for the research is discussed in the present chapter 1.

Chapter-2 contains the detailed description of design, fabrication and testing of a high voltage power supply rated at 20 kV, 22.5 A (output power 450 kW) along with ultrafast crowbar protection system. The rf (Radio Frequency) system of *K* 500 Superconducting Cyclotron (SCC) at VECC consists of 3 nos. of rf cavities (dee) separated at 120^o apart in the median plane. So, this power supply feeds to the anodes to three tetrode tubes (Eimac 4CW150,000E) based rf amplifiers. All the three tetrode tubes are protected by a single ignitron based crowbar protection system against internal arcing in any of the three tubes. During an internal arc fault, a very specialized topology is adopted that diverts the stored energy through an ignitron followed by tripping the input power. The wire burn test was performed for confirmatory test of the crowbar protection system. The chapter presents the salient design features, their simulation, in house development and technical challenges faced during the testing of the high voltage anode power supply and crowbar protection system for the rf amplifiers for SCC which is presented and results of this work have been published in the Journal of instrumentation [6]. Previously, the prototype unit was developed and tested [5]. There were some problems related to heating and high voltage breakdown which was later redesigned for better performance.

In **Chapter 3**, the development of a negative polarity high voltage dc power supplies (-30 kV, 3.2 A) required for biasing the electrodes of Inductive output tube (IOT) based rf amplifier test stand working at 700 MHz in continuous mode has been presented. This power supply is also almost similar to the one as mentioned in Chapter-2 but it is regulated and polarity is negative. The power supply is designed and developed for biasing IOT cathode by utilizing SCR based phase angle controlled topology for the regulation. The crowbar protection system is implemented which is more complex in a negative polarity power converter. Testing of the crowbar system is done by using wire burn method. Other auxiliary power supplies are used are for grid, filament, ion pump, focus coil. The power supplies for grid, filament and ion pump of IOT are with respect to the cathode, floating at high voltage, which have been placed at a high voltage deck and parameters control and monitoring are done through a PLC based system. The design details along with test results of this work have been published in Journal of instrumentation [7].

Chapter 4 is dedicated mainly to the development of a high voltage power supply based on pulse step modulation (PSM) technique for ~60 kW continuous wave (cw) rf amplifier based on Inductive output tube (IOT) TH793-1 operating at 700 MHz. For a nominal beam bias, cathode requires a high voltage power supply (HVPS) of maximum rating -40 kV, 5 A for design and development. The present development is aimed to utilize a modern technique meeting all the required important criteria, ie, modular construction, smaller size, crowbar-less design, reliable operation, voltage regulation with higher efficiency, fast response and most importantly easy to service.

PSM based high voltage power converter (rating -40 kV, 5 A) consists of 60 switched type power modules (SPMs) out of which maximum 52 modules can be switched on and remaining in standby. The voltage is obtained by adding the output voltages of each SPM in series and modulating their pulse widths and phase delay time to achieve higher ripple frequency. This results into very low ripple voltage at high frequency which ultimately requires very small filter capacitor resulting into very low stored energy. That is the reason why PSM based power supply does not require a separate crowbar protection system. Other power supplies for filament, grid and ion-pump are connected with respect to the cathode placed at high voltage deck. Two Ethernet optical fiber media converters connected to a PLC through 5m long optical fibre link for their controls and communications. This work has been published in Sadhana Journal [8] and results are presented.

Chapter 5 describes the study on harmonics and EMI, their basic concepts of generation and side effects. Various journals and publications were studied and presented how Electromagnetic Interference (EMI) becomes a major concern for high power SMPS power supplies and various types of motor drives in electrical field. It causes conducted and radiated EMI noise which creates nuisance for other electronic equipment. Presently, we don’t have in-house practical setups for measurement of EMI, but in future, we will be setting up and perform extensive measurements also.

Finally **Chapter 6** contains the conclusions and perspective of high voltage related works to be carried out at VECC in future. It is also discussed that all the HVPS developed by utilizing the conventional topology will be slowly converted to highly efficient PSM based systems.

CHAPTER 2

Design and development of high voltage power supply for K-500 SC cyclotron high power rf amplifier with crowbar protection.

2.1 Introduction

Tetrode tube based high power rf amplifiers are used in various accelerators to supply hundreds of kW of power to the cavities in the frequency range of few MHz to several tens of MHz. It is because of the simpler and robust design, high stability against frequency variations, higher gain, reliable operation [10,11] and cost effectiveness. The superconducting cyclotron at VECC consists of three cavities separated at 120° apart in the median plane and each cavity is designed to handle 80 kW rf power to produce ~100 kV voltage in the operating frequency range of 9-27 MHz [9] required to accelerate varieties of ion beams. The rf power to each cavity is fed from individual rf amplifier based on tetrode tube (EIMAC 4CW150,000E). The tetrode tubes require dc power supplies individually for its electrodes ie. anode, screen, grid and filament with respect to the grounded cathode. All the power supplies are designed, fabricated, tested and commissioned along with proper controls, ON/OFF sequencing together with the interlocks & protections.

Based on the desired operating region, the ratings of the biasing [12] power supplies are: filament power supply 16 V, 220 A, grid power supply -500 V, 0.1 A with 100 ppm stability, screen power supply 1600 V, 500 mA with 60 ppm stability and a common high voltage power supply rated at 20 kV dc, 22.5 A which feeds power to the anodes of all the three tetrode tubes. The anode power supply is facilitated with suitable interlocks and protections including the crowbar system for the protection of the tubes against an internal arc fault. As per the recommendation, the maximum energy deposition [13-17] in tube must not be more than 50 J during an internal arc fault. To meet the requirement, the stored energy has to be diverted rapidly through a high voltage switch and thus allowing the energy deposition in the tube within the permissible limit.

An ignitron was chosen as a crowbar switch because of its enhanced arc protection feature, faster operation to achieve desired crowbar time, simpler installation, lower turn ON resistance and negligible effect of EMI [15]. A solid state type switch also can be used in place of ignitron. It has some disadvantages, viz. slower turn ON time, complicacy in switching all the series connected SCRs simultaneously and it higher cost. Due to the time constraint to meet the commissioning deadline and final testing of the power supplies with the actual load (rf system of the *K*-500 cyclotron), an ignitron was used. This chapter discusses about the salient design features, in-house development, testing of the anode power supply with crowbar protection system and technical challenges faced during testing.

The bias power supplies for all the three tubes are kept at different locations due to the availability of the space. A schematic layout of locations of the power supplies are shown in **Figure 2-1**. The filament power supplies are located at the basement whereas other power supplies are installed in a room at 1st floor, whereas the amplifier tubes are located in vault at ground floor. It results the use of long power cables and control cables for their interconnections. So, suitable coaxial cables are used with separation between power and control cables in order to minimize the interferences.

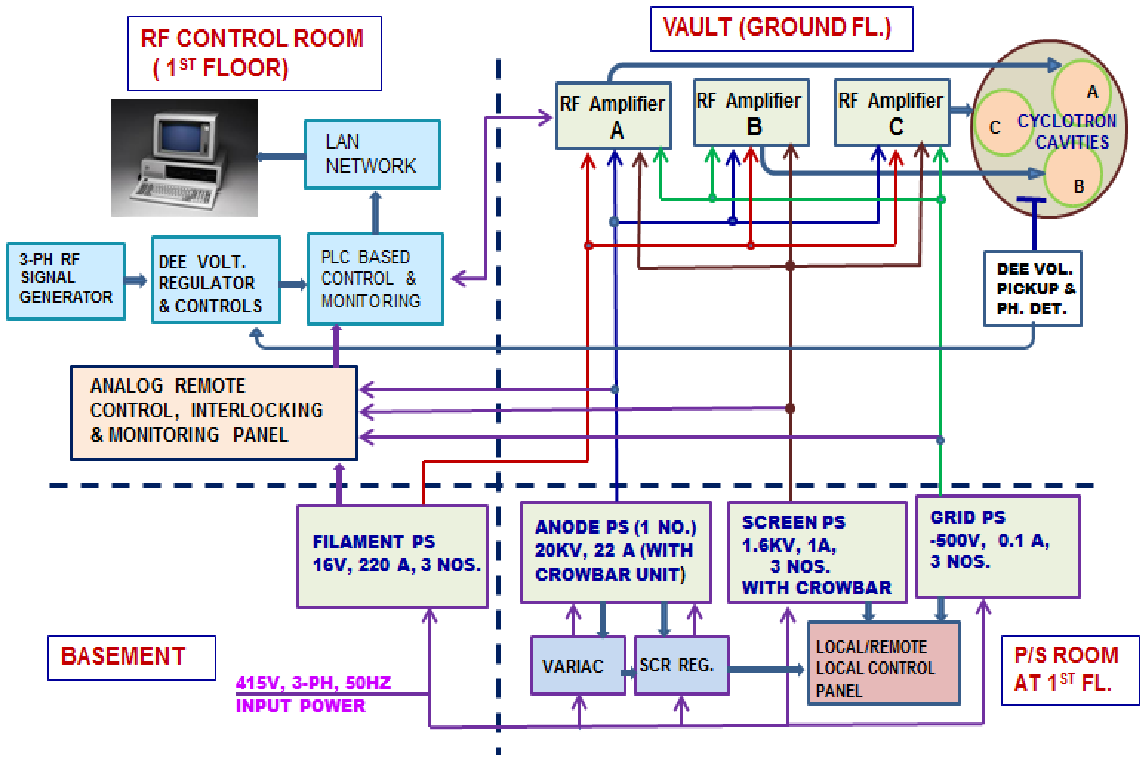


Figure 2-1: Schematic layout of locations of different power supplies and rf amplifiers used in the K 500 Cyclotron building

High voltage power connection from the anode power supply to the anodes of the three tubes are done by using three separate high voltage coaxial cable RG220, each ~25 m cable length through the S-bends. The methodology of high voltage connection for the coaxial cable RG220 is specially developed in our lab which consists of two sets of copper blocks, one for the high voltage and other set the shielding connection at some distance suitable to high voltage level. The control and monitoring of all the power supplies have been done with local console as well as from remote. In local mode, all the operation to the power supplies can be done from the local panel kept in power supply room. In remote mode, parameters control and monitoring is done through Ethernet based Programmer Logical Controller (PLC) installed in the control room.

2.2 Different power supplies for high power rf amplifier

Different power supplies are discussed in this section required to bias all four electrodes of three high power tetrode tubes.

2.2.1 Anode power supply

High voltage power supply (HVPS) rated at 20 kV, 22.5 A feeds dc power to the anodes of all the three tetrode tubes (Eimac 4CW150,000 E). HVPS uses two forced air cooled main transformers and each transformer has delta connected primary rated at 415 V, 3-phase, 50 Hz, 250 kVA power and two secondary windings, one of which in **star** and other in **delta,** to achieve 30° phase shift for 12 pulse rectification. Each secondary has the voltage rating of 3700 V_{L-L}, 3-phase, 50 Hz.

Input 3-phase, 415 V supply is connected to two main transformers via air core chokes (0.1 mH, 400 A) in each line and fast interrupting circuit breakers (CBs) having tripping time 80 ms (4 cycles). Thus total four secondary windings from two transformers are connected to their respective 3-phase full wave bridge rectifier assembly giving 5 kV dc voltage each after rectification [11] and then these are connected in series to provide 20 kV dc at 600 Hz ripple frequency, as shown in **Figure 2-2.** The rectifier assembly consists of 12 avalanche diodes (each rated at 1.6 kV, 40 A) connected in series in each limb. The use of avalanche diode relieves from using series connected R-C network for voltage equalization. Thus all four rectifier assemblies consist of total 288 diodes mounted on individual heat sinks. The heat sinks are fixed on glass epoxy sheet inside a cabinet providing an isolation of ~40 kV and connected to the transformers with high voltage Teflon insulated cable.

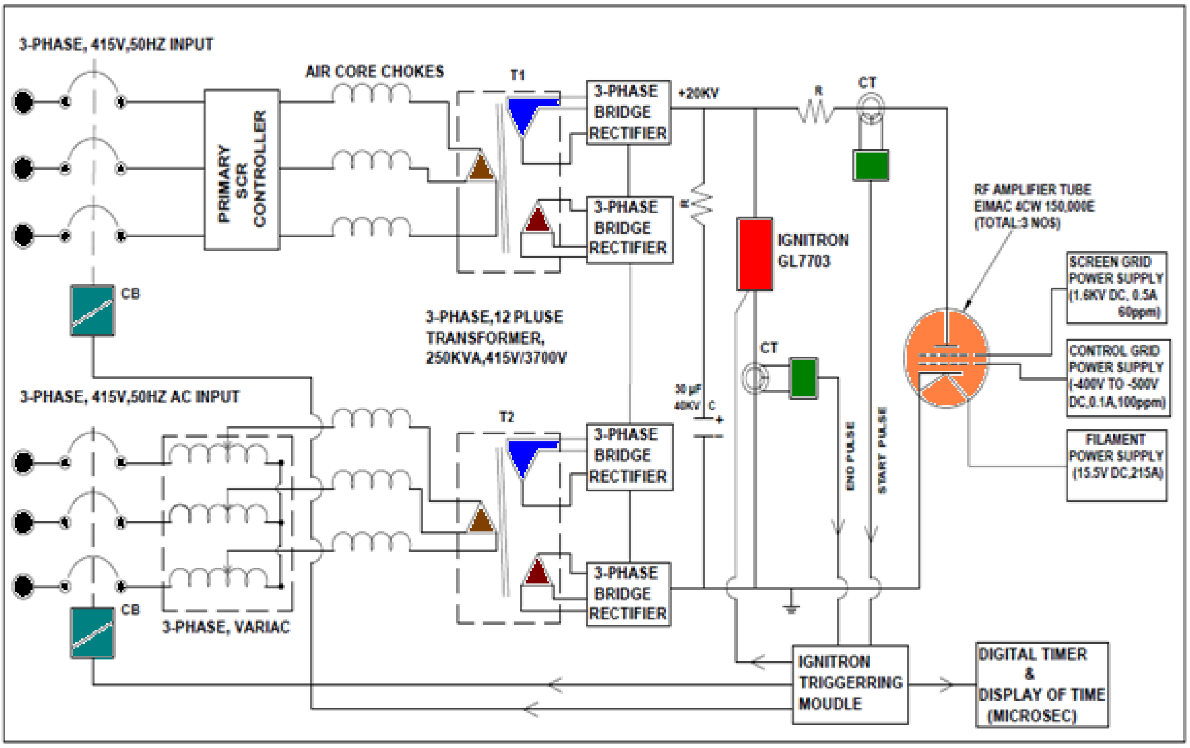


Figure 2-2: Schematic diagram of anode power supply with ignitron and a tube.

A primary SCR controlled soft start feature is incorporated in the primary side of the first transformer to provide half of the voltage, i.e. 10 kV dc. In the primary side of the second transformer, oil cooled, 3-phase, high current (400 A) variac is used to adjust the output voltage on-line between 10 kV to 20 kV dc depending upon the requirements. The protections and interlocks such as, dc over current, input over current, water flow fail in ignitron, over temperature at various components, cooling fan fail, phase fail etc. are implemented along with crowbar protection. Hall type CTs are used for dc over current protection and dc current monitoring for each tube. Pearson current transformers are used to sense the internal arc fault condition in each tube and to initiate the crowbar protection subsequently. Actual photograph of two transformers of anode power supply and Local control panel is shown in **Figure 2-3**.

Figure 2-3: Photograph shows the local main control panel with monitoring and fault indications for all the power supplies and two transformers of anode power supply.

Local control panel has all the arrangements for switching ON-OFF of three set of power supplies for the Filament, Grid, Screen and an Anode along with individual voltage and current monitoring and interlocks indications.

The advantages of using two transformers with double secondary windings are as follows:-

a) Facility to adjust output high voltage from 10 kV dc to 20 kV dc.

b) Less voltage stress on HT winding of transformer.

c) The ripple content is greatly reduced to around 1% by utilizing 12 pulse rectification feature, thus reducing the capacitor filter as well as the stored energy.

d) Less input current harmonic content.

e) Improved input power factor (better than 0.90).

A *p*-pulse converter under balanced conditions generates a characteristics harmonics in input side of the order *h* which [18] is given by **h = pn± 1**, where n is any positive integer. In a 3-phase rectifier system under balanced condition, the expected harmonics are 5^{th}, 7^{th}, 11^{th}, 13^{th} …… which contribute to major part of the distortion in the input.

Total harmonics distortion (THD) will be given by

$$THD = \frac{\sqrt{V_5^2 + V_7^2 + V_{11}^2 + V_{13}^2 + \dots}}{V_1}$$

where V_1 is voltage amplitude of fundamental frequency. The magnitude of harmonics currents (I_h) is given by $I_h = I_1/h$, where h is the order of harmonics and I_1 is the current of fundamental frequency.

The vacuum tubes are very much prone to internal arc fault and costly tubes may become severely damaged if excessive energy is deposited during an internal arc fault. Crowbar system protects the tubes by diverting the excessive stored energy through ignitron, a high voltage switch. Thus, crowbar protection system a very critical and important. During the internal arc fault, the power supply experiences a short circuit condition until main CB trips. The excessive current flowing through the main transformers results a huge mechanical and electrical shock [14-17]. So, while designing the transformer, sufficient factor of mechanical strength of yoke, insulation resistance to withstand high voltage transients and higher % impedance are considered. The transformer with higher % impedance offers more resistance which restricts the short circuit current. Air core chokes in the primary of transformers offer further increase of the impedance which is advantageous in the event of crowbar. **Table 2-1: -** Components details and test results of the anode power supply.

Table 2-1: **-** Components details and test results of the anode power supply

s. no.	parameters	values
1	Output voltage	+ 22.8 kV dc at no load
2	Max output current tested with amplifier tubes at rf load.	17.5 A (at 18 kV dc)
3	Ripple voltage	< 275 V p-p at 18 kV dc.
4	Typical THD in input current	6.7%
5	Input PF	0.95
6	Input Transformer Details (Each of Two Transformers)	Primary- Delta connected, 415 V, 3-ϕ, 50 Hz, 250 kVA Secondary windings- star and delta connected, line voltage 3.7 kV ac.
7	Transformer % Impedance	8%
8	Time of short circuit withstand test on the transformers	5 s
9	Filter capacitor	30 μF (each 3.75 μF, 40 kV, qty:- 8)
10	Rf filter at output of each anode	L= 100 μH, C=250 pf in π configuration

The anode power supply circuit simulation is done and required crowbar time is found to be less than 5 μs considering the load resistance 1000 Ω, as shown in **Figure 2-4**. In this circuit, the ignitron and co-axial cable is modeled [18, 19] for simulation so as to achieve very near to the accurate result.

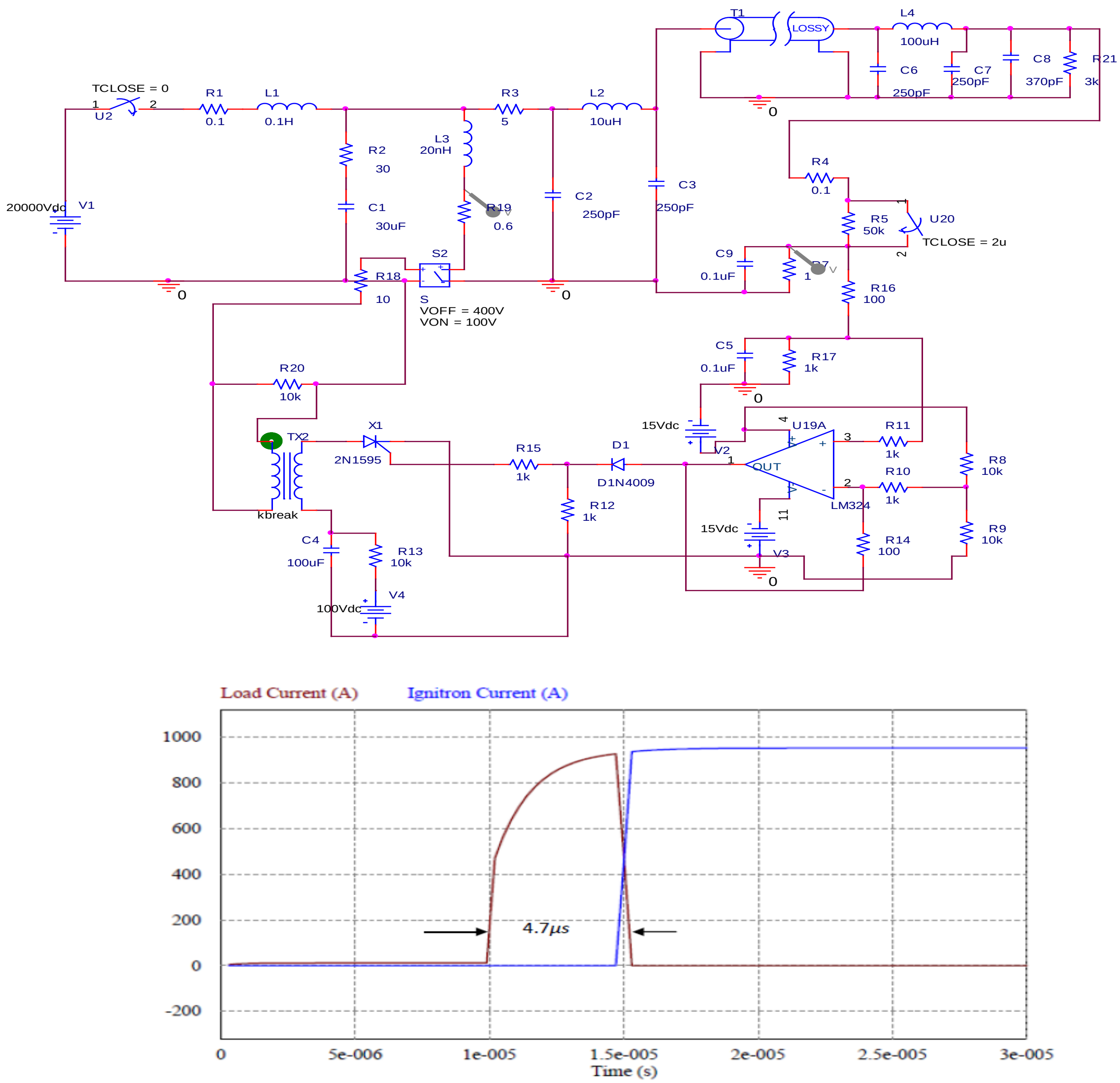


Figure 2-4: (*a*) Schematic diagram of crowbar protection system (*b*) Simulation result of the crowbar protection system of anode power supply.

2.2.2 Screen power supply

Three individual power supplies for the screens of three tubes, each rated at 1600 V, 0.5 A, 60 ppm voltage stability have been designed and developed. It uses water cooled tetrode tube (Eimac 4CW2000) as a regulating device in series, as shown in **Figure 2-5**.

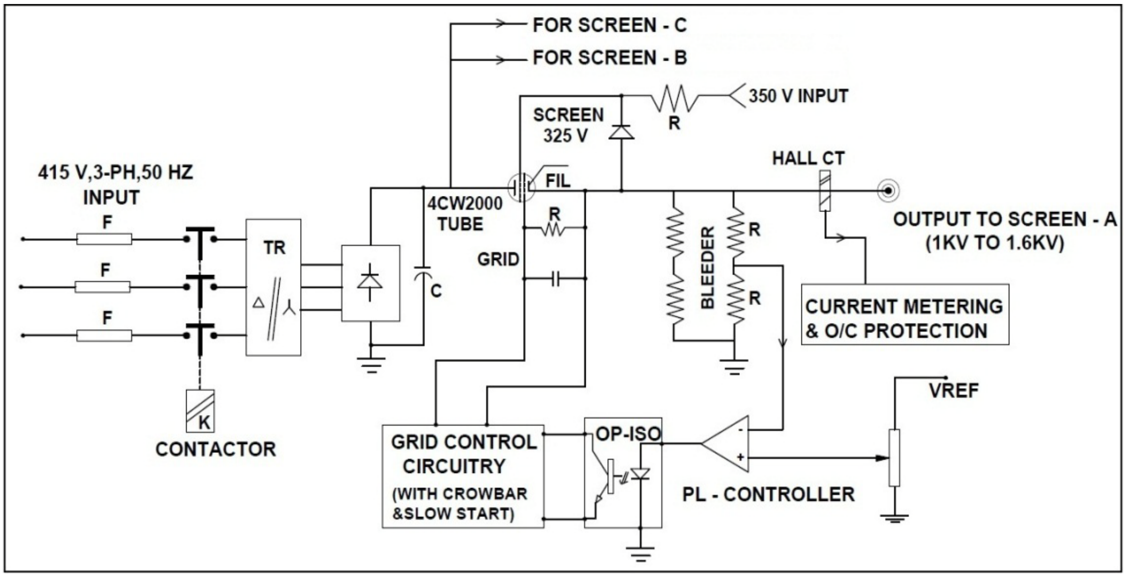


Figure 2-5: Schematic diagram of screen power supplies for the rf amplifiers.

A 3-phase conventional transformer and rectifier is used and then filtered to get 2500V dc for anodes of three regulating tubes connected as series pass scheme. For each series tube, individual power supplies are used for the biasing its electrodes. The electronics circuit for regulation is designed for adjusting the grid of the series tube to maintain the required output voltage. The screen power supply exhibits reverse current under certain operating conditions and to avoid it, the output is shunted with a bleeder resistance of 3 kΩ. In case of a crowbar condition, the power supply fast turns off the screen and protects the system.

2.2.3 Grid power supply

Grid power supply (rating -500 V, 0.1 A, 100 ppm) is a series regulator type power supply which uses IGBT as series element for voltage regulation. Grid power supply is a low ripple and highly regulated power supply with adjustable voltage from zero to -500 V for biasing the grid. Individual grid power supplies are used for three tubes.

2.2.4 Filament power supply

Filament power supply (rated at 16 V, 220 A) is required to heat up the filament which does not need very good regulation. It uses a variac in primary of input transformer for regulation and soft start. It consists of a step down 3- phase transformer, a full wave bridge rectifier followed by an L-C filter. The part of output voltage is sampled and fed back to the control circuit which takes care of voltage regulation by controlling the position of variac. Auto zero of variac and slow ramp up of output voltage is the special feature of the control card which ramps up in steps by controlling the variac from zero to around 80% voltage corresponding to output 15.5 V dc in approximately 3 minutes.

2.3 Crowbar protection system

The crowbar protection system is used to protect the vacuum tubes against an internal arc fault. It detects the fault condition, initiates the corrective action by triggering ignitron very fast and discharges the excessive energy [20]. An ignitron (Part No:- 7703EHV, Make: Richardson Electronics, USA) is used as a high voltage switch which meets the required criteria, i.e. faster response, indefinite hold off high voltage, ability to transfer large amount of charge, low conduction impedance etc. A peak current of ~1000 A flows through the ignitron for short duration of 80 ms till the circuit breakers trip the mains power and results an electron charge transfer less than 1 C per shot [15, 21]. The stored energy (~6 kJ) in the filter capacitor is required to be bypassed through the ignitron and considering the source impedance of the power supply, the conduction of ignitron has to be initiated within 5 μs after the fault. This protection is one of the most critical parts of the high voltage power supply without which the tube can be damaged.

2.3.1 Crowbar circuit block diagram

The key components used in the crowbar protection system are Pearson current transformer (CT), high voltage fast acting crowbar switch, pulse transformer, non-inductive resistors, capacitors, fast SCR, MOVs etc. All these components must be fast acting and suitable for very high frequency applications.

The Pearson current transformer of Model:-110 (Make:- Pearson Electronics Inc, USA) is used to sense fast rise of the fault current with improved noise immunity and isolation from high voltage. It possess wide bandwidth of 20 MHz with 3 dB lower cut off at 1 Hz, sensitivity 0.1 V/A and response time 20ns. The CTs are calibrated at operating dc current level with 1 MΩ termination. Based on the experiments, the additional delay in response time is found to be few ns, which is negligible. This indicates that the dc current level does not drive the magnetic material into saturation and so there is still some flux swing available to generate a signal from the fault current. Several models of CTs are available used at different labs for similar applications [15, 16].

The time delay is measured to be ~2.5 μs between the fault signal sensed by the CT and the pulse transformer output pulse which is reasonably sufficient to trigger the ignitron within 5 μs. **Table 2-2** shows the key specification of crowbar circuit utilized in the present high power rf system. Hall type current transformers (HCT) are used for output dc current measurement purpose and for sensing over current conditions.

Table 2-2: Crowbar circuit specification

SN	Parameters	Values
1.	Stored energy in filter capacitor	6 kJ
2.	Crowbar time between sensing the arc and the triggering of Ignitron.	~5 μs
3.	Limit of energy deposition in the tube during arcing.	50 J, (accomplished by Crowbar Protection System)
4.	Peak current in output at short circuit condition	900 A
5.	CB tripping time	80 ms (4 cycles)
6.	Charge transfer	1 C per shot, through ignitron before CB trips OFF.

The fast rise of the arc fault current in each of the three tubes is sensed by respective CTs. One another CT connected in series is to sense total output current. Thus the isolated signals from four CTs are fed to the crowbar electronics controller card and after conditioning, the signals are compared with a trip threshold voltage. Then the signals are fed to a latching circuitry for visual indication and fault diagnostics. The latched signals are then gated together to generate a mono-shot pulse of duration ~100 ms to trigger a SCR. A capacitor, charged at 800 V, is rapidly discharged through the SCR connected in series with a pulse transformer and output fast rise high voltage (~2.8 kV) pulse so generated is used to trigger the ignitron, as shown in **Figure 2-6**. Simultaneously, crowbar controller card sends

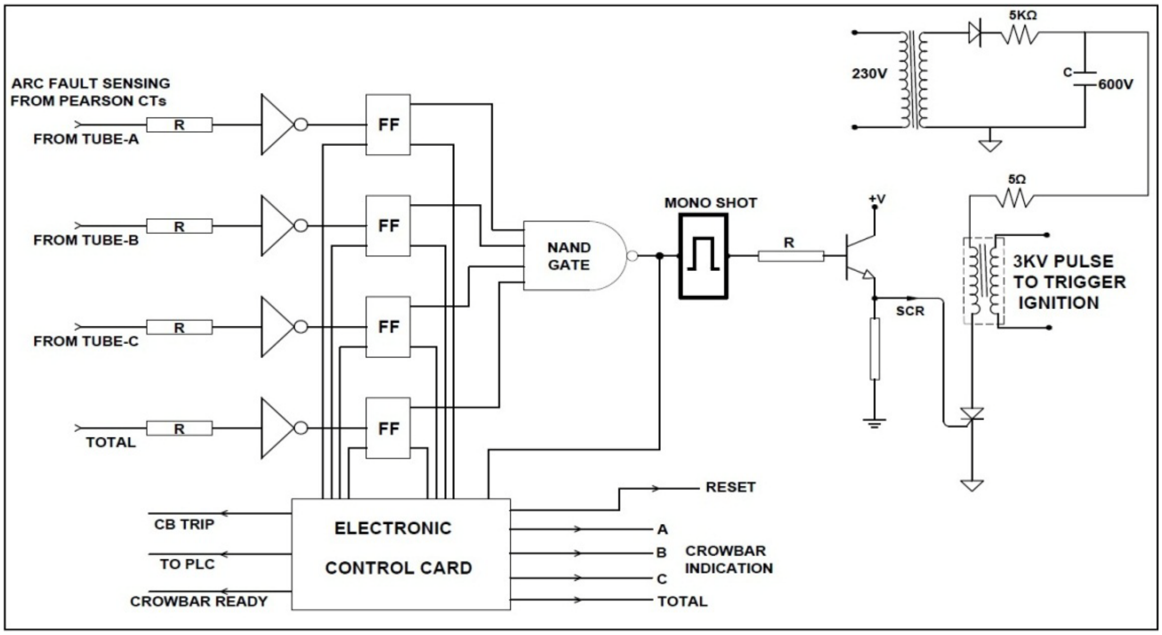


Figure 2-6: Schematic of scheme of crowbar protection system.

a hard wired command to trip the mains power circuit breakers (CBs) and also from the PLC to trip CBs for redundancy. A manual push button switch is also provided for local crowbar testing. After the tripping of CBs, the system can be made ON for the next operation only after a reset from local or PLC.

2.3.2 Timing calculation

During an arc fault, the short circuit current flows through the tube is the sum of currents from filter capacitors and power supply,

$$I_{SC} = I_{PS} + I_C \tag{2.1}$$

where I_{SC} is short circuit current in output,

I_{PS} is the current from the power supply transformer, I_C is the current from the filter capacitors.

$$I_{PS} = \frac{\text{Full load current}}{\text{percentage impedance}}\ \text{x}100$$

$$= \frac{22}{9.5}\text{x}100 \cong 230\text{ A} \qquad (2.2)$$

where total 9.5% impedance is considered for transformer and input chokes.

$$I_C = \left(\frac{V_{c\,max}}{R}\right)e^{-t/RC_{filter}}$$

$$= I_{c\,max}e^{-t/RC_{filter}}$$

$$\cong 667\text{ x } e^{-t/RC_{filter}} \qquad (2.3)$$

where $V_{c\,max}$ is the maximum voltage and RC_{filter} is the time constant of capacitor discharging current, R is the equivalent resistance in series with filter capacitor which is 30Ω. Since, the limitation of energy dissipation is 50 J. So, the crowbar timing can be calculated as:-

$$V_{out} \times I_{PS} \times t_{crowbar} + V_{out} \times I_C \times t_{crowbar} \le 50J \qquad (2.4)$$

$$t_{crowbar} \le \frac{50}{V_{out} \times (I_{PS} + I_C)}$$

$$t_{crowbar} \le \frac{50}{V_{c\,max}(e^{-t_{crowbar}/RC_{filter}}) \times (I_C\,(1-e^{-t_{crowbar}/RC_{filter}}) + 230)} \qquad (2.5)$$

By using the *fsolve* function of MATLAB for solving for the crowbar timing and found to be less than 5 µs. The result is counter checked by plotting power ($V_{out} \times I_{PS}$ + $V_{out} \times I_C$) versus time graph given by Eq. 2.4. The area is calculated by using *trapz* function of MATLAB which gives 4.57 µs crowbar time at 50 J energy.

2.3.3 Test setup and wire selection

The crowbar system performance is checked by the wire survivability test which provides a calibrated measure of energy deposition at load end. The wire fuses during the test, if the energy absorbed by the wire is more than its fusing energy which is fixed for a uniform cross section of fixed length. A thin copper wire of 33 SWG of a length 150 mm is chosen whose fusing energy is ~30 J [18] which can safely measure the energy deposition less than 50 J, the limit of energy deposition in the tube during internal arc condition.

An experimental test setup is made ready by using a high voltage vacuum relay in series with a small length (~150 mm) of thin copper wire (33 SWG wire) and the setup is connected across the output terminals of anode power supply. To conduct the crowbar test, the power supply is energized to the desired level. Then the fault is initiated by closing the vacuum relay and allowing the short circuit current to flow through the wire. The fault signal, sensed by a CT, finally triggers the ignitron and at the same time, a trip command is generated which opens the CBs within 80 ms. If the crowbar system works properly, the thin wire would survive and then it concludes that energy deposition is less than its fusing energy. Similar tests are performed repetitively to check the capability of the crowbar system and its perfect functioning.

The energy of a small length of 33 SWG copper wire is calculated as the function of volume (or length for different wire gauges) by using the heat energy equation as follows.

$$\boldsymbol{Energy = (V \,.\, \rho_{cu}) \,.\, (C_{cu} .(T_m - T_a))}$$

The volume of wire, $$V = \frac{Energy}{\rho_{cu}.C_{cu}.\Delta T} \qquad (2.6)$$

where, ρ_{cu} is the density and C_{cu} is the specific heat of copper and ΔT is the temperature difference. Melting temperature of copper is T_m = 1083^o C, Let, the ambient temperature be 25^o C then the value of ΔT is = T_m – 25=1058 ^{o} C. ρ_{cu} = 8900 Kg/m^3, C_{cu} = 385 J/(Kg×K). Putting all the values in Eq. 2.6, the volume V = 13.88 mm^3 is required to fuse at 50 Joule energy. In our case, the length of wire used is 150 mm whose fusing energy is only 30 J. **Figure 2-7** shows variation of wire length of different wire gauges at a fixed fusing energy.

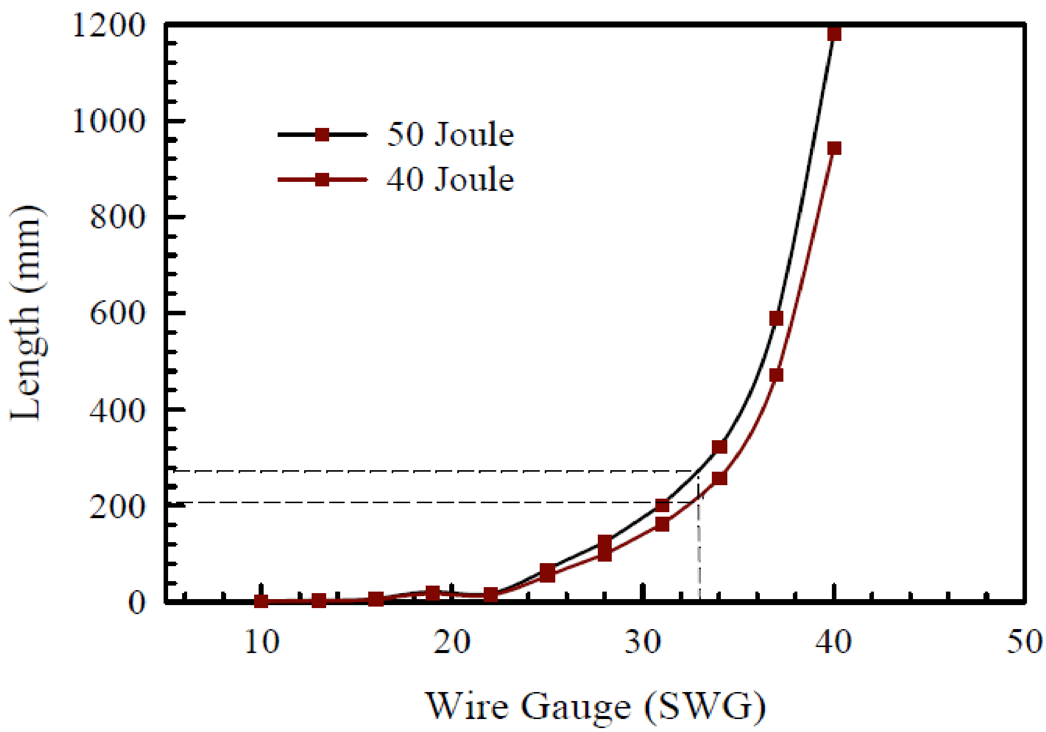


Figure 2-7: Graph showing the calculated length with respect to wire gauge for a fixed fusing energy.

2.4 Data acquisition

The control and monitoring of the rf system including the power supplies are done by using SIEMENS programmable logic controller (PLC) modules. These modules are controlled by a master CPU (CPU 315-2 DP) consisting of a communication processor CP-343-1. This CPU communicates with other modules via Ethernet with maximum 32 modules. In order to monitor/capture the analog parameters of rf system as well as voltages and currents of power supplies, SM-331 module is used. It is an isolated 8 channel, 14 bit resolution analog to digital converter (ADC) having the conversion frequency of 10 kHz. The ADC takes 4-20mA standard current communication for the configuration of different analog signals to be captured. However 6 mA is the lower limit and 18mA is the upper limit is assigned for the calibration. SM-332 is used as a 12 bit isolated and 8 channels digital to analog converter (DAC) which is generally used to provide analog signal from computer to set different parameters of the rf system. Here also 6 mA to 18 mA range is used to provide the anode power supply to set the voltage 0 to 20 kV and similarly for other auxiliary parameters of the rf system. For the control and monitoring of various interlocks, i.e. water interlock, door interlock, over current, over voltage etc., SM-321 and SM-322 modules are used as a digital input and output respectively.

The master device (315-2 DP) based on the PROFIBUS is to communicate with the other slave devices (sensor and actuator). The graphical user interface (GUI) is developed in VECC in java for monitoring and controlling various parameters of sub-systems with 1s refreshing rate.

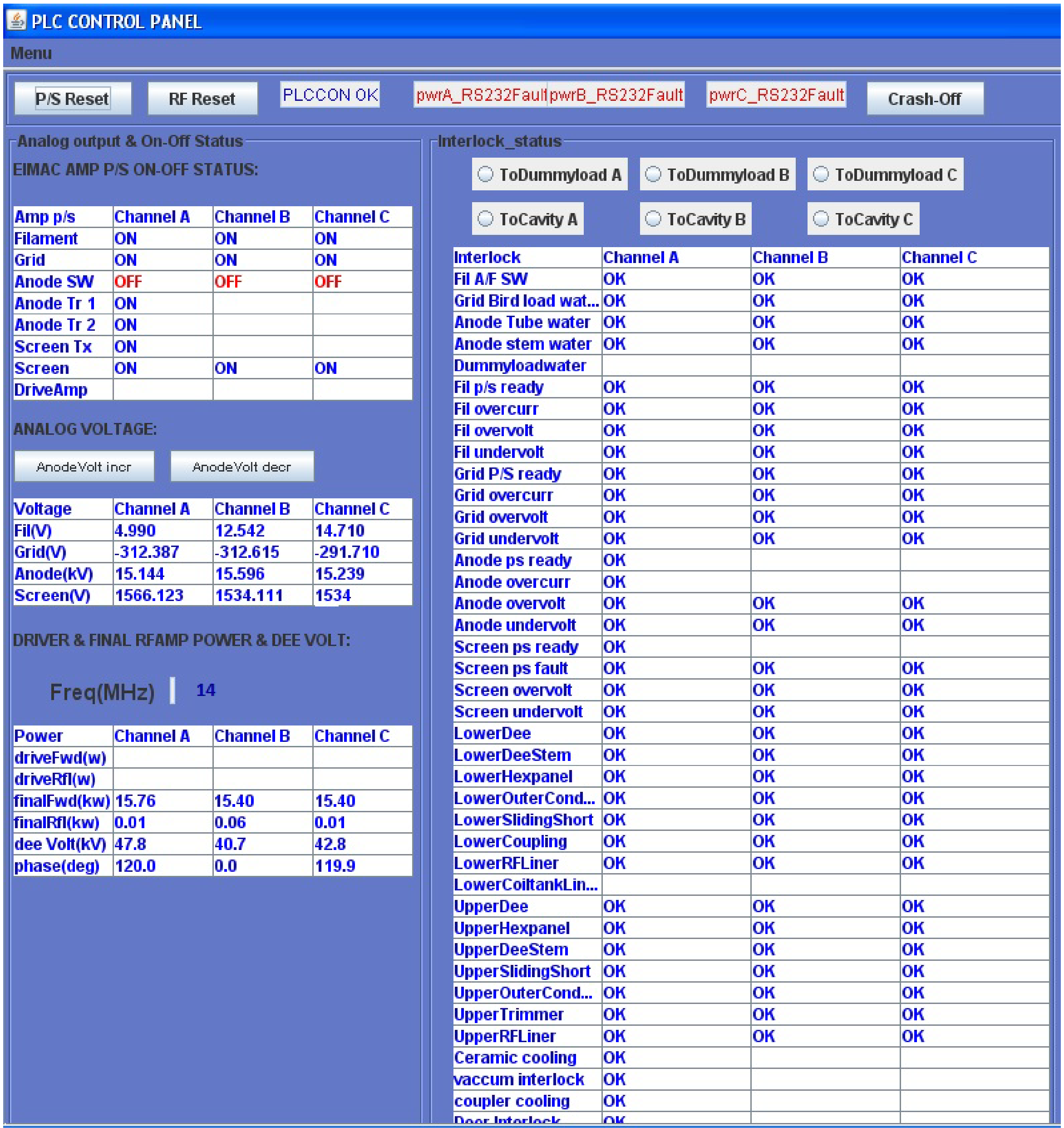


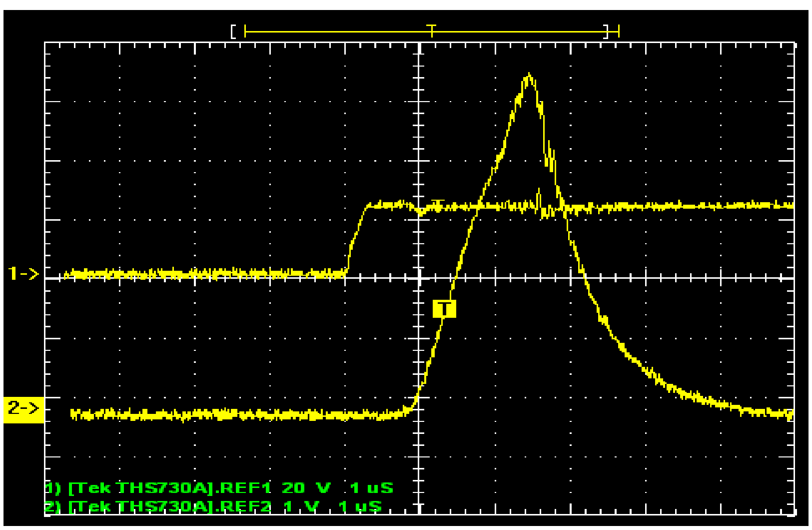
Figure 2-8: RF system control and monitor GUI.

2.4.1 Interlocks and sequence of instruction

The PLC controller checks the sequential operations of related interlocks to make the power supplies ready for ON in proper sequence. It first checks the start-up interlocks, such as low conducting water (LCW), door closed, vacuum, cooling system before the filaments of rf amplifiers are ready for ON. A PLC screen shot is shown in **Figure 2-8** where the parameters monitoring along with the status of interlocks can be visualized. Once all the start-up interlocks are cleared, the filament power supplies become ready for ON. Similarly, after filament, sequence is followed as grid, anode and finally screen power supply. The GUI is made in such a way to follow the above sequence of putting ON the power supplies. Reversed sequence is followed during shutdown.

2.5 Test results and discussion

The system performance and protective capability of the crowbar system is demonstrated by using wire survivability test which gives the measured value of the energy deposition. Initially the card level tests are performed i.e., firing sequence and their respective delays between the signals are carried out at various points.



Time (1μs/div)⟶

Figure 2-9: Ch-1- A 24 V voltage is applied corresponding to a simulated fault (20 V/div), Ch-2- Pulse transformer output showing 2.8 kV pulse at rise time 1.5 μs (500 V/div).

As shown in **Figure 2-9**, Ch-1 shows a dc voltage of 24 V which is applied at the fault sensing input to simulate the fault condition and delays. Ch-2 shows the pulse transformer output voltage 2.8 kV peak with 1.5 µs rise time. The result shows that the delay in response of pulse transformer is 1 µs after the fault and pulse transformer rise time is 1.5 µs. Thus total time delay is 2.5 µs between occurrence of a fault and the trigger pulse to the ignitron.

The wire survivability test with a thin copper wire of 33 SWG of length 150 mm is performed successfully at ~18 kV voltage level in output.

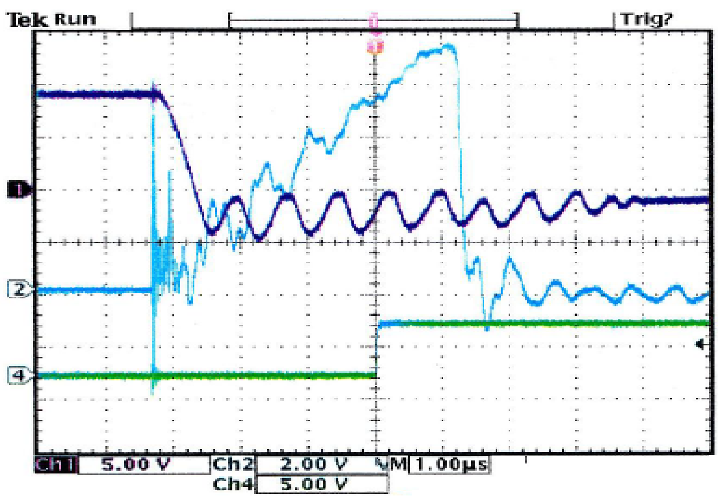


Figure 2-10: Ch-1(top)- output voltage at 18 kV (10 kV/div), Ch-2 (middle)- current flows through wire by using a CT (100 A/div), Ch-4 (bottom)- signal for tripping the CBs simultaneous to the ignitron trigger pulse. X- axis denotes Time scale with 1 µs/div.

The test setup, consisting of high voltage relay in series with thin copper wire, is connected across the power supply output terminals. Output voltage is set at desired voltage level. All other protective systems are kept in ready condition before the fault is created by closing the high voltage relay. The wire survivability tests are successfully conducted.

In **Figure 2-10**, Ch-1 is the trace of output voltage at 18 kV dc before the fault. Ch-2- shows the current through the wire shoots up to ~500 A after the fault occurs. The current will continue to increase till the ignitron turns into full conduction within 5 μs. Ch-3- shows the pulse generated to switch off the CBs simultaneous to the ignitron trigger pulse. The ignitron is triggered within 5 μs and thus the thin wire is survived. The crowbar tests are repeated successfully and that can be enough to conclude the energy deposition at load end within the permissible limit.

2.6 Summary and conclusion

The design, fabrication, commissioning and testing of total power system for all the three rf amplifiers tubes have been accomplished within the stipulated time and total rf systems have been in operation continuously since more than 6 years on round the clock basis for the tuning and beam extraction from the cyclotron. After the installation of anode power supply, heat run test was performed with the tube in dc condition. The power system along with the rf amplifier was tested with water cooled dummy rf load up to 70 kW. The real time measurement of rf system parameter implies the satisfactory operation of these power supplies with the tetrode tube based rf amplifiers.

During the testing of Anode power supply, two major challenges were encountered which were subsequently resolved. All the cabinets are solidly grounded and the components at high voltage level must withstand at least double the working voltage. During the insulation voltage withstand test of high voltage rectifier assembly, some problem was noticed. Excessive leakage current and heavy corona discharge was observed even at lower voltage inside rectifier cabinet which could lead to a voltage breakdown. It was solved by re-mounting the diodes on glass epoxy channel and FRP angle providing more isolation and tested up to 40 kV dc. Next, there were some problems due to the noise. It was also observed that the noise and transients in the output dc voltage was creating spurious triggering. It was resolved by making a dedicated grounding pit and their connections with braided copper conductor with larger cross section. There were some minor problems during crowbar testing. The crowbar circuit design was finally done after some trials by using faster and better components to minimize the delay and finally the desired system response time was achieved and then the wire survivability test could be successfully conducted.

CHAPTER 3

High voltage power supply (-30 kV, 3.2 A) with crowbar protection for Inductive Output Tube based rf amplifier system

3.1 Introduction

Particle accelerator that produces ion beam of energy greater than 20 MeV generally requires a high power rf amplifier source which normally made by either by using solid-state devices or by using vacuum tubes, ie., tetrodes, Inductive output tubes, klystrons, magnetrons, gyrotrons etc. The IOT based rf amplifier is developed for the use to pursue research and development activity in superconducting rf cavity project at Variable Energy Cyclotron Centre (VECC) Kolkata. The state-of-the-art technology of IOT-based high power rf amplifier is designed, developed, and tested at VECC. A high voltage power supply rated at negative polarity at 30 kV dc, 3.2 A is required for biasing cathode of IOT with crowbar protection. As a part of the project, the design and development of high voltage power supply for IOT rf amplifier has been taken up for testing multi cell superconducting cavity.

A test stand was planned to be developed for preliminary testing of IOTs and also for periodic conditioning on regular basis during ideal storage time. IOT has been planned to use as our maximum operating frequency is of the order of 1.3 GHz. IOT based amplifier is most suitable for the medium power and for Ultra high frequency (UHF) range i.e. 300 MHz to 3 GHz.

Various papers and literature survey explain the criticalities of IOT [22-27] based rf amplifier and related power supplies for its biasing. A high voltage power supply of rating around -30 kV, 3.2 A for cathode electrode is needed whose anode is connected to ground. Other auxiliary power supplies are for Grid (-200V/100mA), Ion pump power supply (5kV/1mA), Filament power supply (24V/40A) and Focus coil power supply (12V/40A). Except the Focus coil power supply, all are with respect to the cathode and thus floating at high voltage at 30 kV.

Like other tubes, IOT is very much prone to undergo internal arcing and during this condition, the excessive stored energy from the power supply should be diverted very fast in order to limit the energy deposition in tube. Thus a crowbar protection is very critical and important part of the power supply for the protection of the tube. A high voltage ignitron (NL7703EHV) is used to divert excessive energy for the protection of the tubes. In the present operating conditions, the ignitron should be triggered within 15 μs to limit the energy deposition in tube within its limit. Normally, the tube manufacturer suggests for limiting the energy less than 50 J during internal arc condition [25, 26]. So, for safety, the power supply crowbar system is designed for the energy less than 50 J. The control and monitoring of the whole rf system along with the power supplies are done using SIEMENS make advanced programmable logic controller (PLC) modules. Present chapter describes the design, development and testing of high voltage power supply (-30 kV, 3.2 A) along with crowbar protection system and other auxiliary power supplies for biasing electrodes of Inductive Output Tube (IOT) based rf amplifier.

3.2 Block diagram of IOT based rf amplifier

The block diagram and layout of IOT based rf amplifier system along with its auxiliary power supplies are shown in **Figure 3-1**. The Thales make IOT TH793-1 is installed along with all necessary electrical and services connections i.e. low conductivity water (LCW) lines, ion pump etc. The negative polarity of the high voltage power supply (HVPS) at -30 kV is connected to the cathode electrode of IOT with respect to the grounded collector. The electron beam is formed by a gridded, convergent-flow electron gun and confined by an axial magnetic field. The biasing of the gun is done in such a way so that no current flows except during the positive half-cycle of the rf input. Thus the electron bunches are formed which are accelerated through the constant potential difference between the cathode and anode [22, 23].

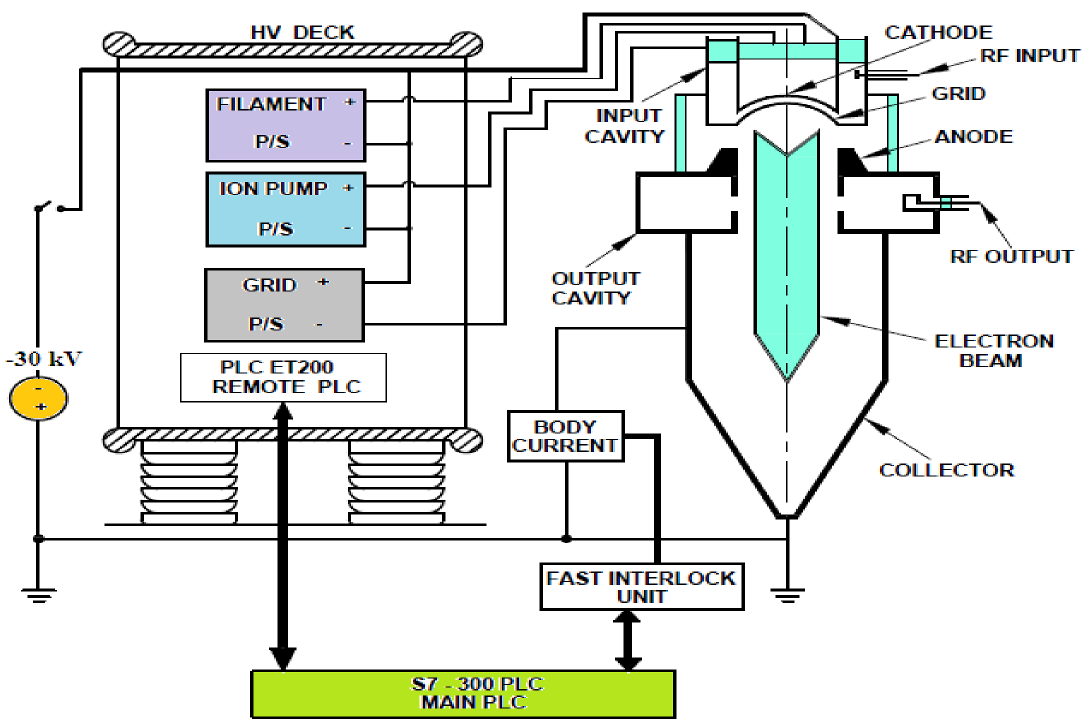


Figure 3-1: Scheme of IOT based rf system with all the power supplies and PLC.

Other auxiliary power supplies such as, filament, grid and ion pump along with I/O modules for their control are installed on a high voltage deck. The motive of putting them on the high voltage deck is to provide high voltage isolation as these power supplies operate with respect to cathode which is floating at high voltage. For monitoring and controlling these power supplies, PLC based data acquisition systems is installed which communicates the command signal via fiber optic cable to the PC. The details of individual systems and their test results are mentioned in following sub-sections.

3.2.1 High voltage deck

A high voltage deck is specially developed for keeping the power supplies, ie. filament, grid and ion pump which are floating at high voltage at 30 kV. Distributed I/O control modules are also kept on the deck for their control and monitoring.

Figure 3-2: Photographs of (A) high voltage deck consisting of three power supplies (Ion pump, Filament and Grid power supply) and isolation transformer at bottom (B) PLC based control system connected through optical fibre link.

The deck is fabricated by using glass epoxy and housed inside a grounded metallic cabinet for safety. The multiple racks have been provided for the power supplies. All the sharp edges are covered with corona guards. The isolation of high voltage deck is tested up to 45 kV. The electrical power for the systems at high voltage is provided by a single phase, resin cast isolation transformer of 4.5 kVA, isolation voltage 45 kV. The photograph of high voltage deck consisting of all three auxiliary power supplies with isolation transformer is shown in **Figure 3-2(A)** and PLC based control system in **Figure 3-2(B)**.

3.3 HV power supply (-30kV, 3.2A)

High voltage power supply (HVPS) is for biasing the cathode of the IOT with respect to grounded anode. A primary SCR based phase angle controlled topology has been adopted for the voltage regulation as shown in **Figure 3-3**. During starting condition, the firing angle of SCRs slowly increases till the required voltage is achieved and at operating condition, these primary back to back SCRs offer voltage regulation by varying the firing angle. HVPS uses two forced air cooled transformers, each having two 3-ph secondary windings connected in star and delta in order to have 30° phase shift for 12 pulse rectification feature. Primary of each transformer is delta connected and rated at 415 V, 3-ph, 50 Hz whereas each secondary rated at 5800 V, 50 Hz. Each secondary connected to a 3-ph bridge rectifier assembly and the rectified dc voltages are then connected in series to achieve rated output voltage, like our previous HVPS [6].

This feature helps us in getting less ripple voltage at 600 Hz, less harmonic content in supply current and improved power factor. Input 3-phase, 415 V, 50 Hz is connected to the transformers via circuit breakers (CBs), air core choke (0.3 mH) and back-to-back SCRs in each line. In order to produce 30 kV dc, each secondary of the transformers uses 3-phase full wave bridge rectifier assembly that gives ~7.5 kVdc after rectification which is finally connected in series to produce 30 kVdc.

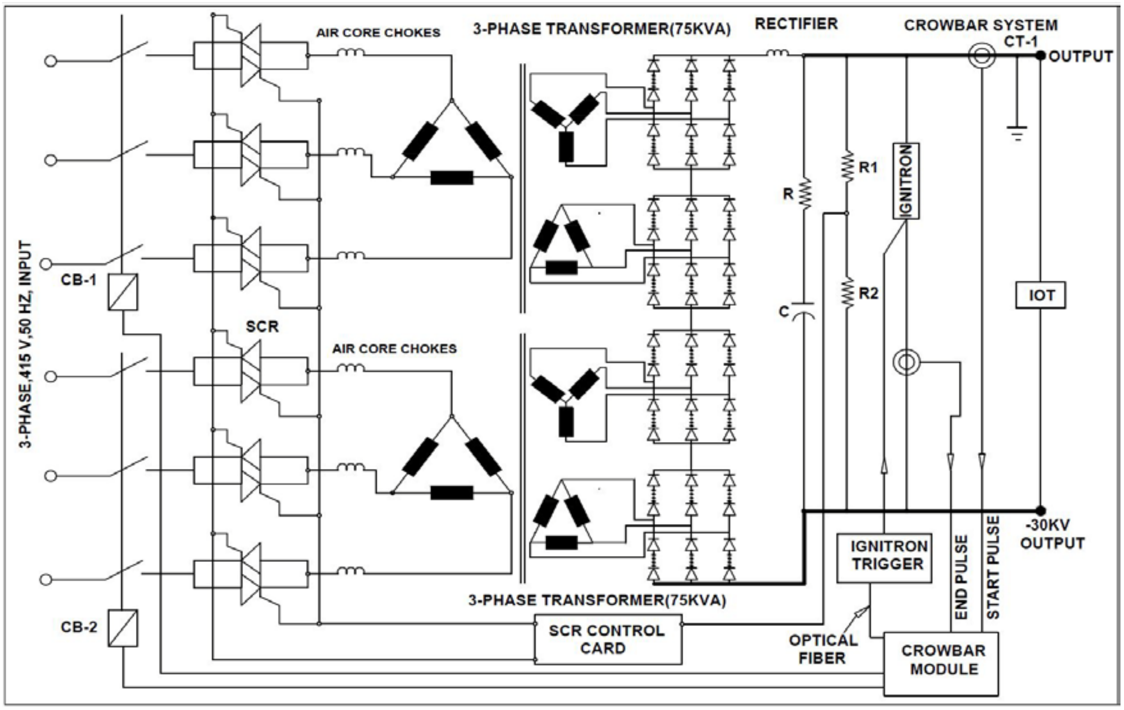


Figure 3-3: Schematic diagram of HVPS (-30 kV/3.2 A) along with crowbar protection.

Peak reverse voltage in each limb of rectifier assembly experiences a voltage of 8.2 kV ($5800\sqrt{2}$). Each rectifier limb assembly, consisting of 10 series connected avalanche diodes, each diode rated at 1.6 kV/ 12 A and thus peak inverse voltage rating of diode series combination is 16 kV assuming around double safety margin. A filter capacitor of value 3.8 μF, 60 kV is used. The output is connected to the cathode through rf filter connected in π-configuration.

The power supply experiences a short circuit condition during crowbar very frequently, so air core choke is required to limit the short circuit current by introducing a voltage drop across it. The choke may be connected in the input side or in the secondary

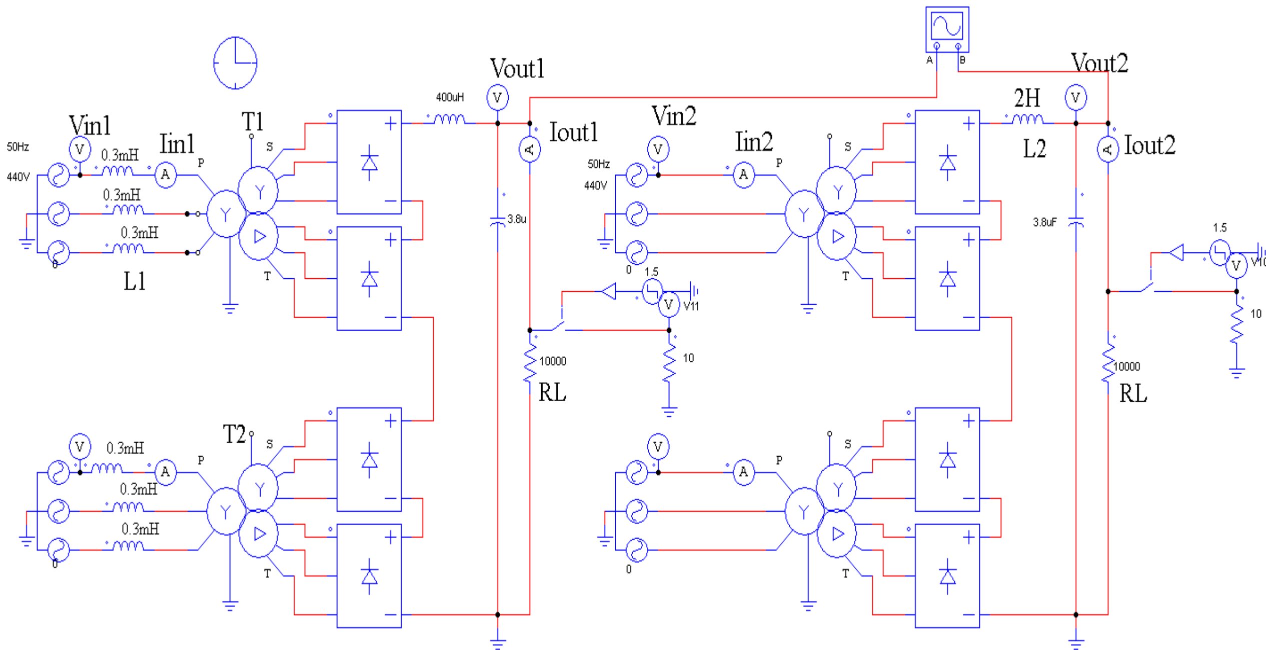


Figure 3-4: Simulation schematic for cathode power supply.

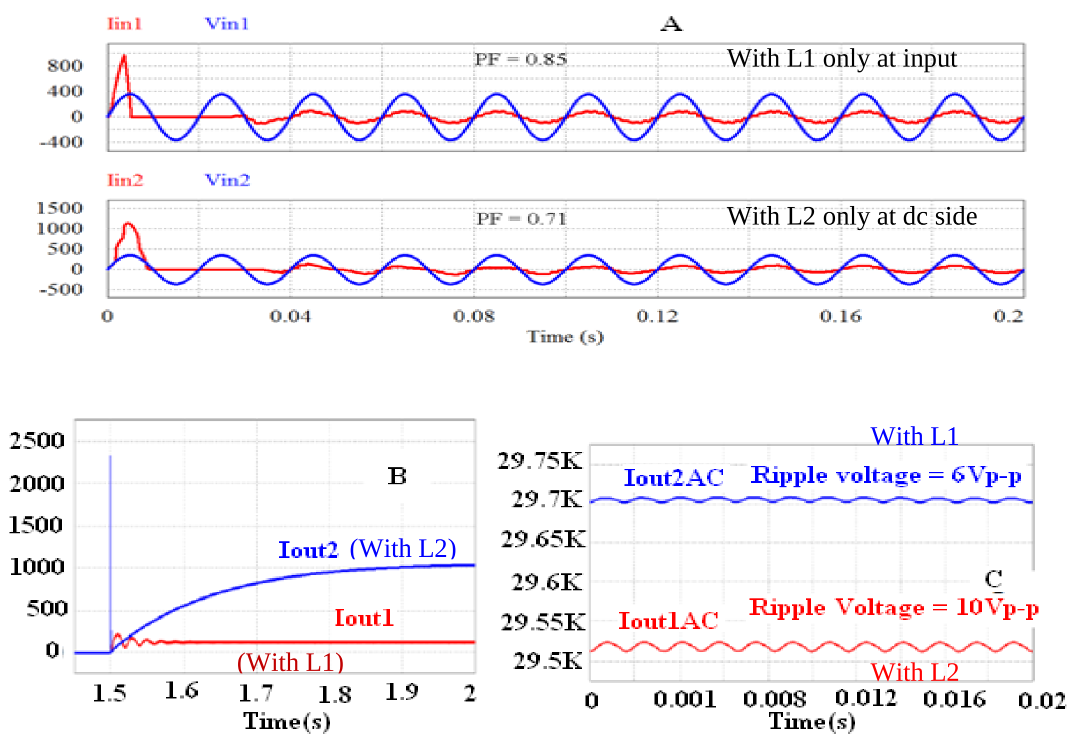


Figure 3-5: Simulation result shows (A) improvement of power factor (B) the reduction of input side current during short circuit condition and in (C) reduction of ripple voltage.

side after rectifier assembly. The circuit diagram is shown in **Figure 3-4** and simulated with air core choke (L1 = 0.3 mH) connected in input lines and compared with the equivalent choke (L2 = 2 H) in secondary side as L-C filter. The simulation is performed using PSIM software for both conditions and simulation results shows improved power factor in case of chokes at primary side (0.3 mH) rather than equivalent inductor 2H referred to the secondary side, as shown in **Figure 3-5 (A)**. It is also observed that introduction of primary side choke reduces the initial short circuit current as well as output ripple voltage, as shown in **Figure 3-5 (B)** and **Figure 3-5 (C)**. Finally, air core chokes, each rated at 0.3 mH, 250 A, are connected in each line of the primary side of the transformer.

Primary side choke value is optimized in such a way to add more impedance for more voltage drop across it during short circuit without much affecting the regulation during normal operation. By this way, short circuit current level will be reduced. So, as a tradeoff between these two parameters, approx. 50% of line voltage drop (415*0.5 = 207 V) across it is assumed during short circuit condition. The transformers are rated for primary current 102 A at full load and percentage impedance 8%. So, transformer may experience maximum primary short circuit current (I_{SC}) = 102x100/8= 1275 A. Thus, theoretical calculation gives the choke value

$$L1 = \frac{207}{2.2\pi f \cdot Isc} = 0.28 \text{ mH} \tag{3.1}$$

Thus, air core choke of value 0.3 mH is optimized which will create a voltage drop of ~10 Vac across each choke at full load current. This will cause an extra voltage regulation of maximum 4% which is permissible for our requirements. The input choke when referred to secondary side of transformers and equivalent value of filter choke value is calculated to be ~2 H. **Table 3-1** shows the specification of main cathode power supply.

Table 3-1: Specifications of high voltage power supply for IOT cathode

S.No.	Parameters	Values
1	Max. output voltage	0 to -30 kV dc
2	Output current	3.5 A,
3	Input voltage	415V AC ± 10% , 3 phase, 50 Hz
4	Mains transformer details	No. of transformers= 2 Nos. Each rated at 75 kVA, primary delta at 415 Vac and 2 secondaries in Star & Delta each at 5800 V ac V_{L-L}, frequency 50 Hz. Tr. configuration Dy11d0. Tr. % impedance= 8%.
5	Filter capacitor	3.8 µF, 60 kV
6	Ripple voltage (p-p)	<0.5%
7	Load regulation	< 0.5% (for 10% load variation)
8	Line regulation	< 0.5% (± 10% of input AC variation)
9	Input PF	~ 0.95
10	Shutdown time during fault condition	< 15 µs crowbar followed by CB trip within 250 ms.
11	Energy limitation	< 30 J, Initial stored energy = 1800 J
12	Remote interface	RS-232 / 485 based communication with PC and Graphical User Interface (GUI) for operation and monitoring.
13	Safety interlocks	Input over current, over voltage, dc over current, phase fail, crowbar protection, ignitron water flow, over temp of power components, door switch open.
14	Over current setting	110% of rated current.

3.4 Other power supplies for IOT

Apart from cathode power supply, other auxiliary power supplies are required for the biasing of the IOT. These are Ion pump power supply rated at 5 kV/1 mA, Grid power supply rated at -200 V/100 mA, Filament power supply rated at 24 V/40 A and Focus coil power supply rated at 12 V/40 A. All of the above mentioned power supplies are based on switching type having features such as, voltage and current regulation and computer controlled. Except Focus coil power supply, these power supplies are kept at high voltage deck and input power is fed from an isolation transformer. A PLC based system is kept at high voltage deck which controls and monitors these power supplies through an optical fibre link and a GUI is made to control all the power supplies through the PC.

3.5 Supervisory control and monitoring

The supervisory control and monitoring of the IOT based rf amplifier system has been done remotely in computer via Graphical user interface (GUI) developed in Labview software. The Labview software bridges the gap between application software to actual driver signal. These signal finally control and monitor the SIEMENS make PLC modules. The optical fibre link has been used for transferring control signal from one potential to other high potential (HV deck) or vice versa. A PLC module (CPU 315-2DP) is used as a master controller that takes the optical signal coming from remote PC. After processing the signal, it addresses the PLC which acts as slave device for monitoring and controlling interlocks, auxiliary power supplies etc. SM-331 module is used to capture analog voltages that are used for monitoring purposes. It is an isolated 8 channel, 14 bit resolution analog to digital converter having the conversion frequency of 10 kHz.

For controlling the device, module SM-332 is with 12 bit resolution for digital to analog converter. At a time 12 channels can be controlled using SM-332. The loop time of the data acquisition system is 10 ms. It would be worth to mention that the whole IOT based rf system follows the sequence of operation during start up. It first checks interlocks for start-up, such as low conducting water (LCW), door closed, vacuum, and cooling system before turn ON of the IOT power supplies starting from Filament.

3.6 Crowbar system for IOT based amplifier

The crowbar protection is very important and crucial system for the protection of high power amplifier tubes against internal arc fault. A high voltage crowbar switch is connected across the output tube which is used to bypass the energy during an internal arc.

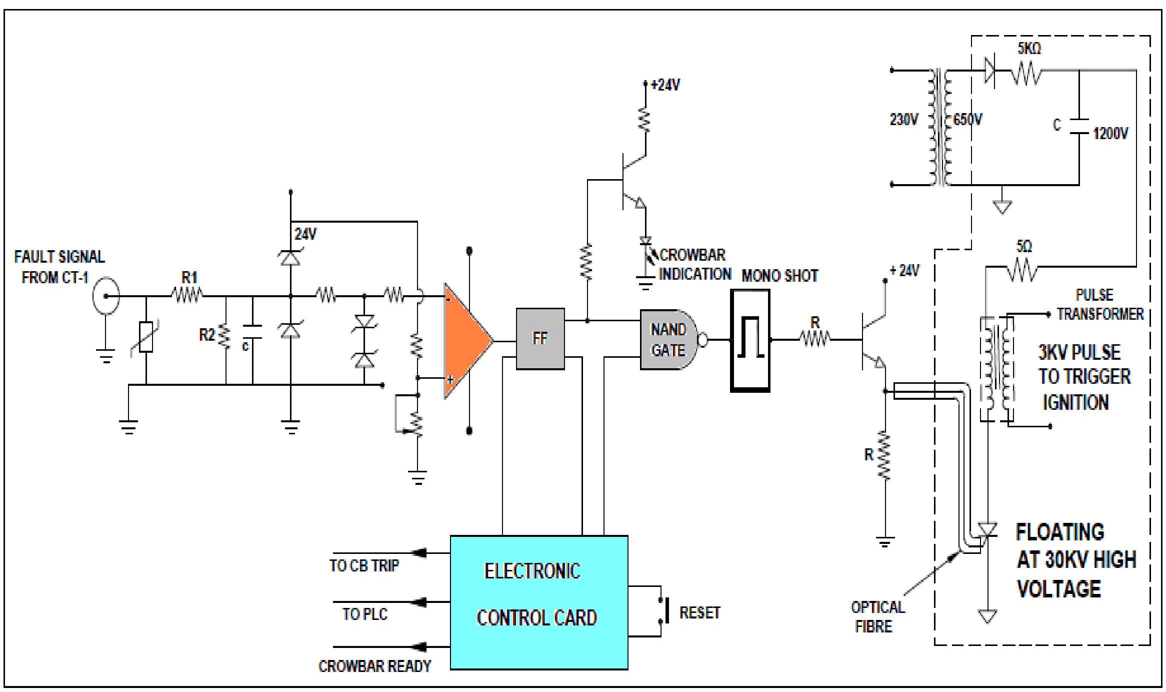


Figure 3-6: Scheme of crowbar protection system

An energy diverter topology is adopted by using an ignitron (NL7703EHV) to bypass excessive energy through it very fast within 15 μs time. The crowbar control unit senses the fault condition and triggers the ignitron very fast and the time delay is a critical factor which amounts to energy dump. The schematic diagram for crowbar protection system is shown in **Figure 3-6**. In this case, to limit the safe amount of energy less than 30J, the ignitron must be triggered within 15 μs followed by tripping off the CBs. During crowbar, transformer experiences a short circuit current resulting a huge electrical and mechanical shock.

With refer to the schematic diagram shown in **Figure 3-3**, based on the stored energy in the filter capacitor during normal operation, the ignitron trigger time must be less than 15 μs followed by tripping off the CBs for attaining the safe limit the deposition of [28, 29] energy across the IOT TH793. The time can be calculated [6] as:

The total current flow during short circuit (I_{sc}) during arcing is represented as:

$$I_{sc} = I_{pl} + I_{fc} \tag{3.2}$$

I_{pl} is transformer short circuit current and I_{fC} filter capacitor current. I_{pl} can be obtained as:

$$I_{pl} = \frac{Transformer\ \ full\ load\ current}{Transformer\ \ percentage\ impedance}$$

$$= \frac{7.3}{8\%} \cong 91\text{A} \tag{3.3}$$

where transformer series impedance is 8% including input chokes. I_{fc} is calculated as:

$$I_{fc} = \frac{Voltage\ across\ \ filter\ capacitor(V_{om})}{\text{Re}\,sis\,\tan ce} e^{-t/RC_{filter}}$$

$$= I_{cm} e^{-t/RC_{filter}}$$

$$\cong 115\, e^{-t/RC_{filter}} \text{ A} \tag{3.4}$$

V_{om} is the maximum voltage appear across capacitor during short circuit and I_{om} is the maximum current. RC_{filter} is the time constant of power supply which is around 1 ms. In order to limit the energy less than 30 J across IOT, crowbar time t_{cb} can be calculated as:

$$V_{out} \times I_{pl} \times t_{cb} + V_{out} \times I_{sc} \times t_{cb} \leq 30J \tag{3.5}$$

$$t_{cb} \leq \frac{30}{V_{om}(e^{-t_{cb}/RC_{filter}}) \times (I_{fc}\ (1 - e^{-t_{cb}/RC_{filter}}) + 91)} \tag{3.6}$$

From MATLAB optimization toolbox, *fsolve* function is used to find the value of t_{cb} of Eq. 3.6 and simulated crowbar timing calculated to be around 18μs. The photograph of the ignitron and electronic circuitry to sense and trigger crowbar is shown in **Figure 3-7**. The heating lamp is placed over ignitron's anode to keep the anode temperature more than that of the cathode. This makes fast settling of mercury inside the ignitron and helps the ignitron to act quickly during an internal arc fault condition in the IOT tube.

As being a negative polarity of HVPS, the anode of ignitron is connected to the grounded positive terminal and cathode is connected to the negative terminal at -30 kV. Since, the igniter of ignitron and other parts of the crowbar protection system including pulse transformer, water cooling system float at high voltage at 30 kV, which is shown in **Figure 3-6**. This makes the ignitron assembly a challenging task starting from fixing the ignitron, maintaining high voltage isolation of more than 30 kV for the crowbar and their on-line testing. Crowbar system consists of mainly Pearson CT, ignitron NL7703EHV, pulse transformer, non-inductive resistors, inverter grade high voltage SCR, low ESR capacitors, MOV etc. The CT (Pearson Electronics Inc, USA, Model:- 110) of response time 20ns is used to sense the fault current with improved noise immunity at a sensitivity of 0.1 V/A. The fault current is sensed by CT-1 and the fault signal is fed to the crowbar electronics card.

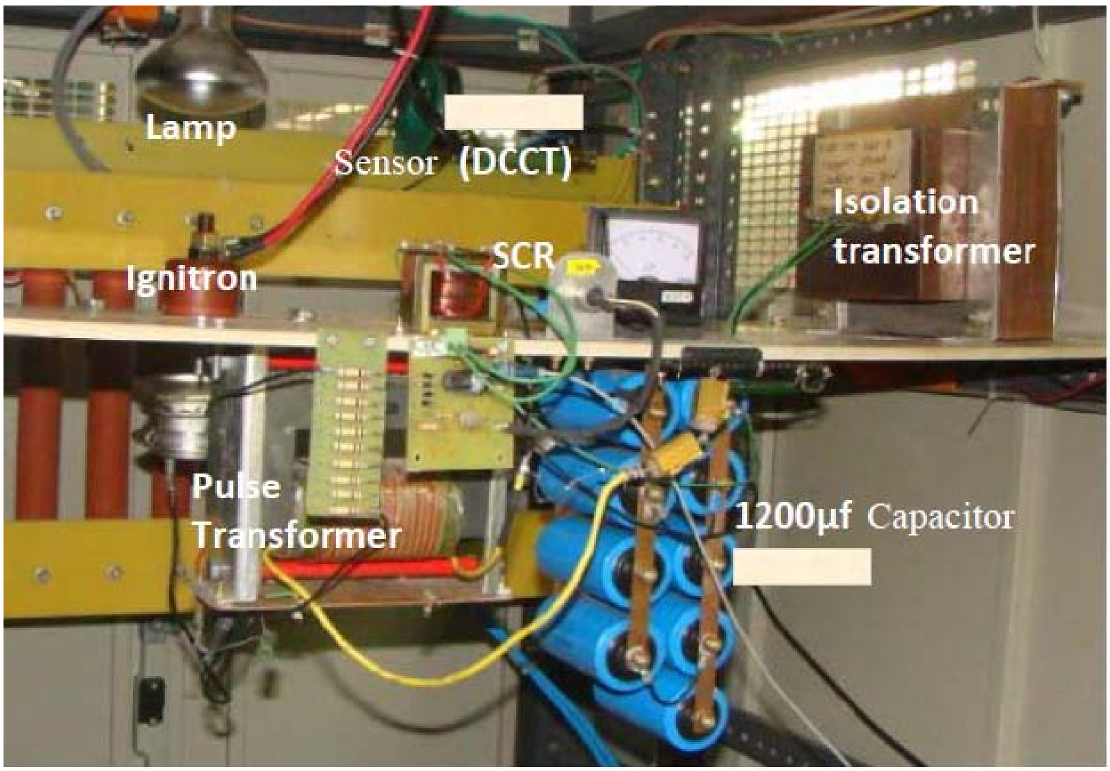


Figure 3-7: Electronic circuit that senses and trigger crowbar

After conditioning, the signal is compared with a trip threshold voltage by a comparator and then it latches for interlocking and visual indication. Finally the latched signal generates a mono-shot pulse (ON time ~1 ms) to trigger a SCR through an optical fiber for isolation. The SCR rapidly discharges through primary of a pulse transformer to generate a pulse of 2.5 kV to trigger the ignitron. Simultaneously, crowbar controller card generates a command to trip the mains circuit breakers (CBs). After every internal arc fault, CBs are tripped and the system is again made ON after reset from local panel via PLC.

3.6.1 Wire survivability test

Wire survivability test is done to check the crowbar performance at test bench before connecting to actual crowbar to the tube. In the present case a thin copper wire of 33 SWG of a length 140 mm is used which has fusing energy < 30 J for testing crowbar of IOT tube. This test gives the information of energy deposition on load. As the name suggest wire survivability test is carried out by passing the short circuit current through the wire and if the deposition is within the safe limit, wire should survive. The test procedure and wire calculation steps are already described in chapter-2.

3.7 Experimental results and discussion

Photograph of the power supplies and all the arrangements are shown in **Figure 3-8** which shows HVPS cabinets along with high voltage deck, IOT assembly, water cooled rf dummy load etc. Initially, the HVPS and all other auxiliary power supplies were first tested individually with resistive load. The auxiliary power supplies were then installed at the high voltage deck along with the control modules and coupled with PLC at ground through fibre optics. The high voltage power supply for cathode (at -30kV) was tested and also other parameters were checked with resistive load as mentioned in Table-3-1. The IOT and water cooled rf load were installed and connected with water line and power supplies. After ensuring interlocks functioning, the power supplies were put on sequentially and the systems were tested with the rf load.

Figure 3-8: HVPS in 3 cabinets, cabinet-1 consists of two CBs for transformers, SCRs, control cards and panels. Cabinet-2 consists of Transformers, six air-core chokes, rectifier assemblies. Cabinet-3 consists of filter capacitor and crowbar unit consisting of ignitron assembly, water cooling.

The system was tested up to rf power ~ 42 kW in several steps and all the power supplies were performed very nicely by keeping the cathode voltage at -30 kV and feeding input rf signal at 700 MHz to the grid.

In order to check the performance of crowbar system, an experimental setup was made by using a high voltage vacuum relay in series with a small length (~140 mm) of 33 SWG copper wire, connected across the output of HVPS. A fault was created by closing the vacuum relay. The performance is demonstrated by using wire survivability test which gave the measured value of the energy deposition less than 30 J. Initially, crowbar cards and the propagation signal delay of the components was tested without high voltage. As shown in **Figure 3-9(*a*)**, Ch-1 shows the initiation of fault and Ch-2 shows the pulse transformer output voltage of 2.5 kV peak with 4 µs rise time after a delay of 3 µs. Time scale is 5 µs/div. Thus total 7 µs delay is recorded between the fault and ignitron trigger pulse. The trigger signal from pulse transformer is fed to the ignitron through a co-axial cable. The crowbar test result tested with 33 SWG copper wires at -27 kV output voltage as shown in **Figure 3-9(*b*)**. Similar tests were performed repetitively to check the capability of the crowbar system and its proper functioning.

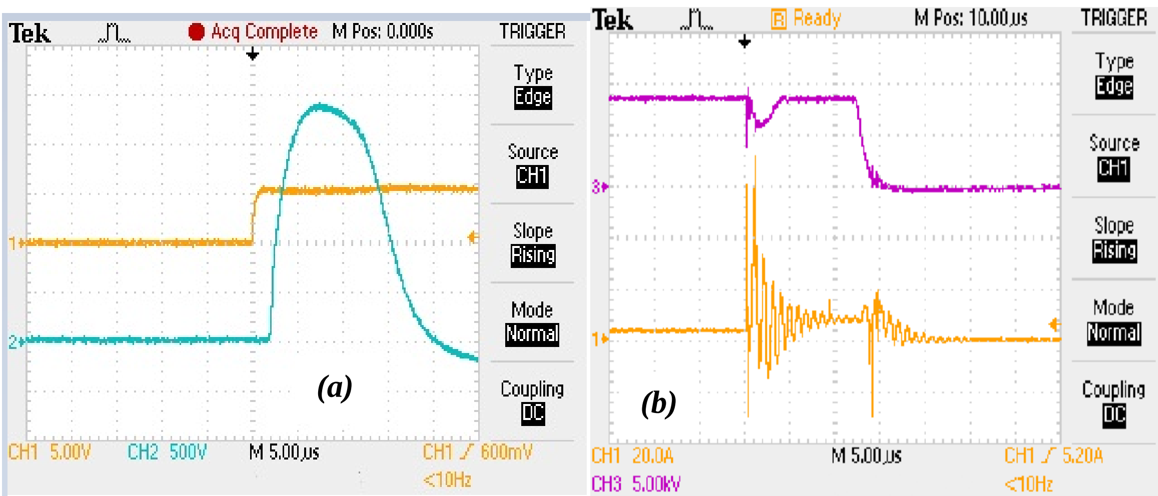


Figure 3-9 : (*a*) Ch-1-The moment fault was created (5 V/div), Ch-2- Pulse transformer output pulse of 2.5 kV having rise time 4 µs (500 V/div). Horizontal axis indicates time scale 5 µs/div (*b*) Ch-1- shows the current profile at 200 A/div and ch-2 shows the output voltage at 15 kV/div by using a potential divider. Horizontal axis Time scale is 5µs/div.

3.8 Summary

The HVPS and test stand of IOT-based amplifier system is designed, developed and tested successfully in VECC. Cathode power supply along with crowbar protection system was tested with the tubes up to the rated current to perform heat run test. The supervisory control of the IOT based rf system was also checked and ran successfully with one or two PC hanging problem. The PC hanging problem was then removed by carefully isolating high potential and low potential grounds and by providing proper shielding to EMI prone components. The primary concern of the design was to keep lower level of short circuit current by incorporating the input air core chokes. Observing the simulation results the optimized value of input core choke is chosen as 0.3 mH in the primary side. Other important feature that is discussed is the development of crowbar protection system for a negative polarity HVPS which is comparatively more difficult than positive polarity power supply. The crowbar circuit worked successfully after several iterations and finally the crowbar timing can be optimized to be within 15 μs. The initial sparking in the high voltage deck was removed by mounting suitable corona guards and high voltage resistance to the floated devices kept at high voltage deck.

CHAPTER 4

Crowbar less high voltage power supply rated at -40 kV, 5 A based on pulse step modulation (PSM) technique

4.1 Introduction

Several high voltage power supplies developed for different systems of the cyclotrons at VECC have been discussed in chapters 2 and 3 by using conventional method to achieve the regulation, ie., SCR based phase angle controller and by using variac. These power supplies have been running on round the clock basis and overall performances are very much satisfactory. In such schemes, as usual, the main disadvantages observed which are huge power loss, lower efficiency, slow response and high stored energy. This would result into implementation of ignitron based crowbar protection system which is a very critical system for the protection of amplifier tubes against internal arc faults.

In the present chapter, a new and emerging technique has been utilized to develop a high voltage power supply rated at -40 kV, 5 A based on pulse step modulation (PSM) technique [30-33]. Still the commercial availability of PSM based high voltage power supplies are limited and are very expensive. In future also, there are requirements of several high voltage power supplies (HVPS) of various ratings for different accelerator applications. It was then finalised to develop the technology of high voltage power supply in-house exclusively for the use in accelerator. This initiative would not only reduce the manufacturing cost considerably but also this will facilitate for the easy and faster maintenance during a breakdown condition. Present development is aimed to utilize a modern technique meeting all the important criterions, i.e. solid state based modular construction, crowbar-less design, reliable operation, improved voltage regulation, higher efficiency, fast response and most importantly easy maintenance.

There are very few manufacturers in the world who manufactures high voltage power converters utilizing PSM based technique. After going through the literatures and articles, a design scheme for high voltage power supply was worked out and the control strategy was finalized. Subsequently, a prototype high voltage system of rating 2.5 kV, 3 A based on PSM was developed which uses a multi secondary transformers with 4 secondary windings to power four SPMs modules. DSP based controller was used which communicates through optical fibre links to all the modules. All the parameters of the power supply were tested successfully and voltage regulation was achieved better than 0.8%.

This follows the design of actual unit of high voltage power supply (HVPS) rated at -40 kV, 5 A based on PSM topology in similar fashion. HVPS consists of 60 switched power modules (SPMs) and each module gets input 3- phase power from multi-secondary transformer’s secondary. Maximum 52 SPMs are required to be switched on and remaining 8 modules are kept in standby which can be automatically put into operation in case of failure of any of the running SPMs. Solid state SPM uses an IGBT in series as a buck converter with a typical output voltage of 780 V at a fixed duty cycle at switching frequency 5 kHz. The operation involves switching-on the required number of SPMs and the output voltage can be obtained by modulating their pulse widths and phase delay time. This results into very low ripple voltage at high frequency which ultimately requires very small filter capacitor resulting into very small stored energy. Hence there is no need to implement a special crowbar protection system. Other advantages of using PSM topology are modular design, low EMI, less harmonics content, high efficiency [34, 35]. The fine control of output voltage setting and regulation is accomplished by pulse width modulation (PWM) of 2 SPMs with variable dc voltage. DSP based control system is developed by using DSP TMS320F28335 in order to ensure the trouble free operation of the power supply as well as option for future upgrade without much change in hardware. In case of a failure of any module, automatically controller will switch on a healthy one after disabling the bad module and thus enabling it to reduce down time.

4.2 HVPS description

In this section, various components of the high voltage power supply is described in details

4.2.1 Scheme of HVPS of rating -40 kV, 5 A

The IOT cathode needs a regulated dc high voltage power supply with low ripple and low stored energy. The negative polarity of HVPS based on PSM is used for biasing the cathode of IOT whose detailed specification is mentioned in **Table 4-1**. The HVPS should be well protected against any of the faults as mentioned, including crowbar. Major components of HVPS are the multi-secondary resin cast multi secondary transformers, switched power modules (SPMs), circuit-breaker, high voltage switch, DSP based control system etc., as shown in the schematic diagram in **Figure 4-1**. The photograph of HVPS is shown in **Figure 4-2**, where all the 60 nos. of SPMs and other accessories are housed on glass epoxy structure and two resin cast multi secondary transformers in rear side and connected to the modules by using high voltage Teflon cables.

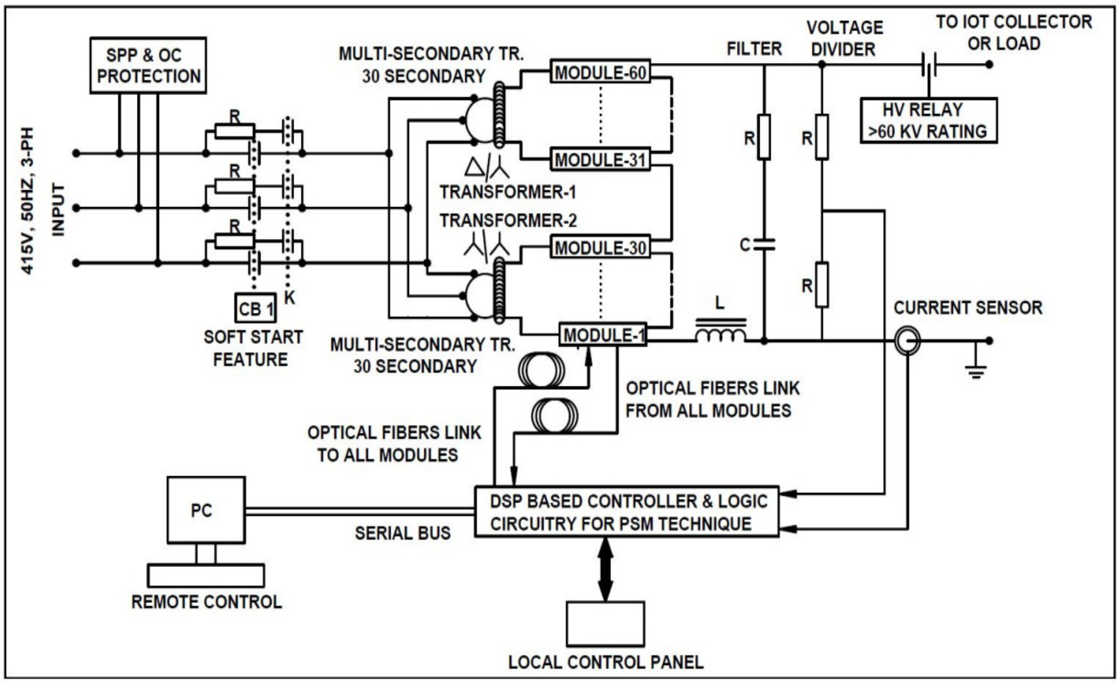


Figure 4-1: Schematic diagram of HVPS rated at -40 kV, 5 A.

Figure 4-2: HVPS showing all 60 SPMs and two resin-cast transformers rear side.

Table 4-1: Specifications of HVPS based on IOT requirement

SN	Parameters	Values
1	Input voltage	440 V AC ± 10% , 3 phase, 50 Hz
2	Max. output voltage	Up to -40 kV dc
3	Output current	4 A, (max rating 5 A)
4	Ripple voltage (p-p)	<0.5%
5	Load regulation	< 0.5% (from 10% to 90% of load)
6	Line regulation	< 0.5% (± 10% of input AC variation)
7	Input PF	~ 0.90
8	Output voltage rise time	< 250 ms (from 0 to Vmax)
9	Shutdown time during fault condition	< 20 μs
10	Stored energy	<30 J
11	Typical overall efficiency	Better than 90%
12	Remote interface	RS-232 / 485 based communication with PC and Graphical User Interface (GUI) for operation and monitoring.
13	Output interlocks	Over voltage, over current, short circuit due to internal arching, module failure, IGBT over temp.
14	Mains input side interlocks	Under voltage, over voltage, over current, phase fail.

4.2.2 Multi secondary transformers

HVPS uses two resin-cast multi-secondary transformers, each having 3-phase star connected 30 secondaries rated at line voltage 580 V, 50 Hz, to power all 60 SPMs which are kept at glass epoxy structure. The primary of one transformer is star and other is delta connected whereas all the secondary windings are star-connected to obtain 12-pulse rectification feature to reduce harmonics content in input current and low ripple voltage at ripple frequency 600 Hz. The transformer's 30 output secondary coils on each limb are kept at equal separation from each other. To provide high voltage insulation, these are then resin casted after vacuum impregnation to avoid any moisture or dirt. The insulation level of secondary coils with respect to primary coil as well as core is maintained at 80 kV whereas between two consecutive secondary coils is maintained at 5 kV. The stray capacitances C_{SP} between primary to secondary windings and C_{SS} between secondary windings are the key parameters and smaller the values of stray capacitances, better the results [36, 37]. The photograph of resin cast transformer mounted in a cabinet is shown in **Figure 4-3**. For the efficient cooling, two fans are connected on the top of the cabinet.

Figure 4-3: Actual photograph of a multi-secondary transformer, having overall dimension (1700x650) mm, H= 1600mm.

4.2.3 Switched power modules (SPM)

Each SPM consists of a soft start feature by using contactors, 3-ph full wave bridge rectifier, filter capacitor, free-wheeling diode, IGBT (SKM75GB176D), snubers, varistors, LEM current sensor and a control board. Each module uses an inductor at output terminal to stop to enter the surge current. The HVPS contains total 60 SPMs and each is fed power from multi secondary transformer's outputs individually at line voltage 580 V, 50 Hz as shown in **Figure 4-4**.

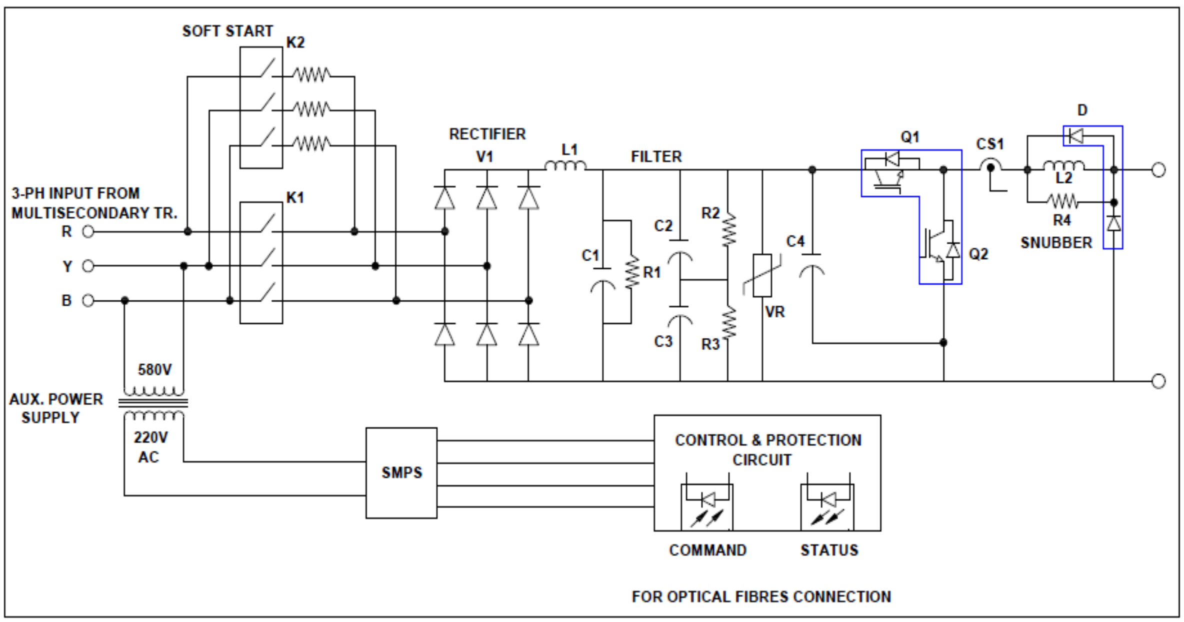


Figure 4-4: Schematic diagram of a SPM

Each SPM consists of soft start feature to avoid a starting surge and EMI due to it. Input 3-ph, 580 V_{L-L}, 50 Hz from each secondary winding of multi secondary transformer is fed to the input via contactor and then rectified by using a 3-ph bridge rectifier. Then L-C filter is used to minimise the AC component of voltage and current present in power supply after rectification. Inductor L_2 is used to prevent any spike to enter due to high inductive reactance to AC, but quite low resistance to dc. Ripple increases with increase in the load in an inductor filter, but decreases in capacitor filter for an increase in the load. So, the *LC* filter is used which is independent of load current or load resistance (R_L). A critical/minimum value of inductor (L_c) is required to insure a continuous conduction mode. This can be estimated using the following well known formula: $L_c \geq \frac{R_L}{3\pi f}$ where, f is ripple frequency. Now the value of C can be calculated by formula, $Ripple = \frac{\sqrt{2}}{3\omega^2 LC}$. In present case a ripple of 0.1% is assumed and accordingly C can be calculated.

Each module is switched type regulator connected in buck configuration by using an IGBT in series and designed for an output of 780 V at 80% duty cycle at switching frequency 5 kHz. The switching frequency is chosen much higher than the line frequency to reduce the size and weight of the output filter. However, with the increase in switching frequency, switching loss and magnetic core loss increases. The switching frequency of each module is kept at 5 kHz which is an optimum value for an IGBT. Ultimately the ripple frequency at output will become *N* times 5 kHz, where *N* is nos. of modules, which is sufficiently high and thus filter requirement is very small.

The output voltage is 780 V when IGBT Q1 is turned-on and zero voltage when IGBT Q1 is turned-off and during off time, the freewheeling diode bypasses the module by providing a bypass current path for others. In case of crowbar or any fault condition, the series IGBT Q1 is turned off and IGBT Q2 is turned on for faster discharge. The control electronics is designed to interface for communication with the main controller through optical fibers and allows the switching of IGBTs from local or remote mode. The series connection of all 60 modules leads to a relatively high complexity of high voltage cable and optical fiber connections. Two SPMs are made vernier modules utilizing PWM type switching voltage regulator for fine regulation. These SPM's output voltage varies typically from zero to 780V depending upon the duty cycle. The control system is developed as per the algorithm and accordingly a GUI is developed for smooth operation and parameters monitoring on remote PC. During the operation, due to the proper modulation strategy, the output ripple frequency seen by the load equals to switching frequency multiplied by number of modules. This feature allows the higher output ripple frequency at lower switching frequency. The control cards of SPM takes care of an effective protection in case of any internal faults and keep the status of health of modules informed to the main controller through optical fiber communication.

4.3 Control scheme of PSM based HVPS

In this section the detailed control architecture of PSM based HVPS will be discussed apart from the mathematical calculations, the main flow diagram that will ensure closed loop feedback by using a controller by using DSP TMS320F28335 and then the supervisory control will be discussed.

4.3.1 Working principle of PSM

There are *N* number of SPM modules, each consists of a dc source *Vs*, a solid-state switch S_i and a freewheeling diode D_i, where *I* denote the number of SPM modules from 1 to *N*, as shown in **Figure 4-5**. The total output voltage across load is the sum of the respective output voltages of each SPM. The output voltage equals *Vs* for a closed switch *S* and zero for an opened switch *S* for any SPM. In coarse step modulation (CSM) control, the controller switched on *n*SPMs (where $n \leq N$) in order to get output voltage nV_s. The problem arising with this approach is that we can get only integer value of *Vs* at the output. But sometime fine steps are to be added and for this, we have added two SPMs for fine-tuning. The difference between required output voltage and CSM voltage is added with PWM-pulses, which are generated just by switching on additional steps.

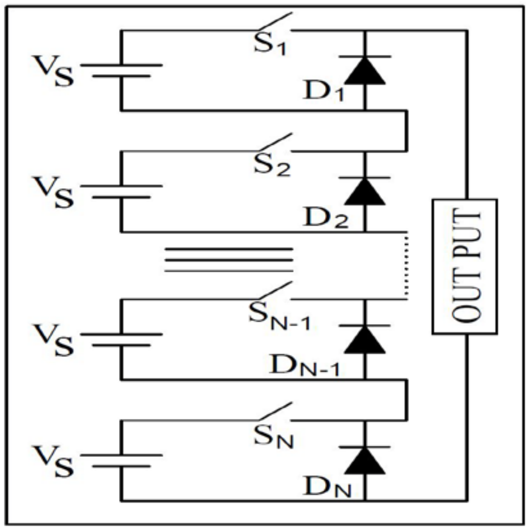


Figure 4-5: Working principle of PSM based HVPS.

Simulation results of four SPMs operated in PSM approach is shown in **Figure 4-6**. Each module has equal duty cycle with a fixed phase shift to ensure equal loading. It can be seen that the output voltage reaches 4*Vs* with peak to peak ripple voltage equal to one SPM voltage (*Vs*) at a ripple frequency four times SPM switching frequency. Thus it would require 16 times less filter capacitor value that could inherently reduce the stored energy and therefore easing the need of additional crowbar protection system. At full voltage, the number of modules will be further increased resulting very low stored energy. Hence, HVPS utilizing PSM technique does not require an additional crowbar system and thus it is called crowbar less power supply.

Assuming total output voltage V_o, delay time T_d consecutive SPM the efficient frequency f_o and modified duty cycle D_o can be calculated as follows.

$$T_d = \frac{T}{N} \tag{4.1}$$

$$V_o = NV_s \frac{T_{on}}{T} \tag{4.2}$$

$$f_o = Nf_s \tag{4.3}$$

$$D_o = (T_{on} - mT_d)Nf_s \tag{4.4}$$

where f_s is the switching frequency of one SPM and N is the number of working SPM. V_s, T_{on}, T, T_d and f_s are input voltage, switch on time, time period, delay time and switching frequency respectively. N is the total number of switch-on SPM and m is the integer part of T_{on}/T_d. So the output voltage and efficient frequency can be adjusted by changing V_s, T_{on} and f_s [38-42].

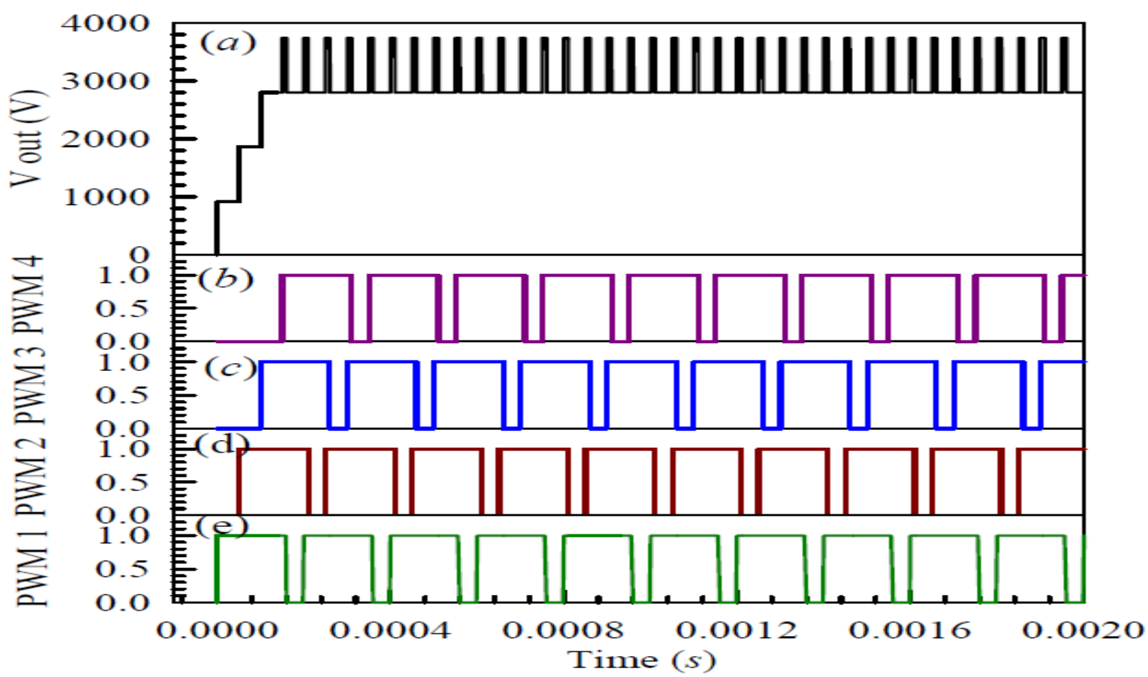


Figure 4-6: Output voltage waveform with shifted PWM for 4 SPMs

As shown in **Figure 4-6**, the output voltage with 4 SPMs at switching frequency f_s = 5 kHz, V_s=780 *V* at duty cycle of 80%. As control signal of the PSM is based on stage rotation, therefore the second switch will turn-on *T/4* time later than the first one, the third will turn on *T/4* later than second one and forth is turned on *T/4* later on than third one and so on. The output waveform (V_{out}) shows that ripple voltage (peak to peak) is equal to one module voltage V_s and ripple frequency equals to four times f_s. From Eq. 4.4, the duty cycle at the output stage is 20%.

Thus the output waveform resulting from PSM modulation gives more advantages. For N=3, keeping other parameter constant T_d =T/3, ripple voltage at output stage is equal to one module voltage, duty cycle at output stage D_o=28%. Similarly, for N=8 Duty cycle D_o=40% and T_d =T/8. Thus, Duty cycle of output stage depends on *m* i.e., integer part of T_{on}/T_d. If T_{on} is integer multiple of T_d, $D_o=0$ output is absolutely ripple free. For N=4, T_d= 50μs, there are four possible T_{on} (50μs, 100μs, 150μs, 200μs) for which $D_o=0$ so, the filter capacitor requirement is almost nil. Hence, in case of four modules there are four duty cycle points where output is ripple free. Similarly, in *N* number of power modules there are *N* duty cycle points where output contain almost no ripple voltage [43, 44]. This strategy avoids or minimizes the output filter capacitance requirement resulting very low stored energy.

4.3.2 Closed loop control program

HVPS consists of total 60 SPMs out of which 58 SPMs having fixed duty cycle and 2 SPMs having variable duty cycle incorporating PWM at switching frequency at 5 kHz for output voltage regulation. During the load disturbances, the difference between required output voltage and Coarse Step Modulation voltage is added with PWM-pulses and gives the output voltage within 200 V of set voltage. In order to realize the precise timing control of the PSM modules, Texas Instrument floating point Digital Signal Processor TMS320F28335, as shown in **Figure 4-7,** is used as the core controller to generate pulses for switch-on and switch-off IGBT for each module. DSP communicates with each SPM through optical fibre as all the SPMs are floating at high voltage.

The DSP has special purpose CPU that provides ultrafast instruction sequences such as shift and add, multiply and add which is commonly used in math operation. Also, it has inbuilt circuit made up of PWM, Analog-to-Digital Converter (ADC) and Input-Output (I/O) peripherals. These circuit peripherals are mainly used as a controller for the power electronic converters. The DSP controller is used because of its advantages, i.e., low cost, embedded floating-point unit, high clock speed, high resolution, on-chip ADCs, high performance PWM unit. Code composer studio (CCStudio) IDE v3.3 software is used for the programming of TMS320F28335 [45]. It is the integrated development environment (IDE) for TI's DSPs. It includes compilers, source code editor, project build environment, debugger, profiler, simulators and many other features.

Figure 4-7 : TMS320F28335 with PWM output and Analog input

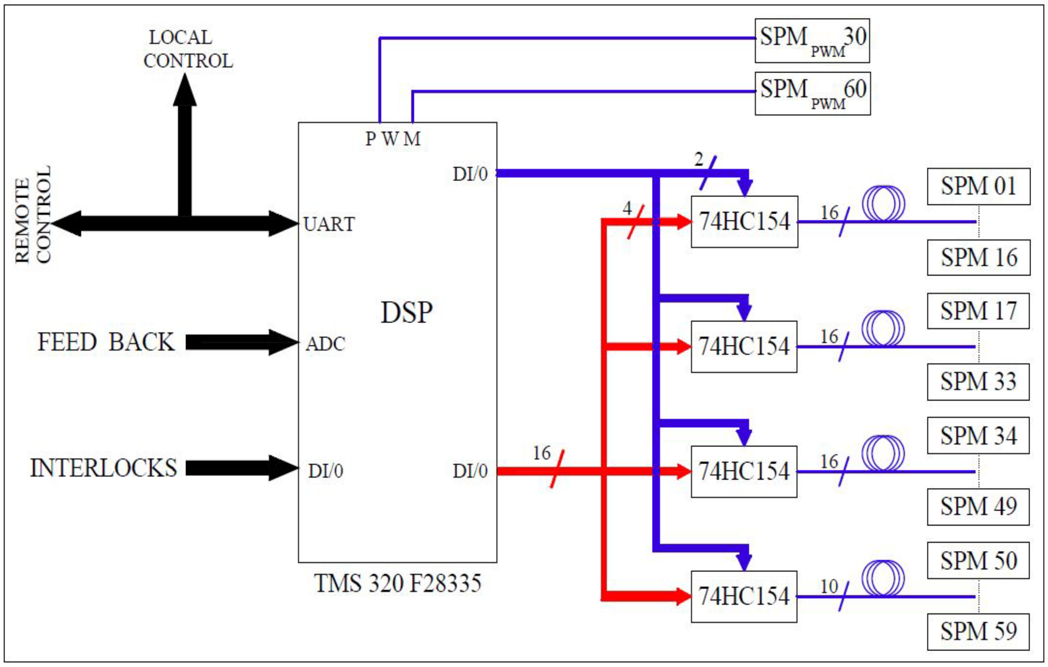


Figure 4-8: Block diagram of DSP based HVPS control architecture

ADC input channels are used to receive the feedback of voltage and current signals. Four to sixteen lines multiplexer (74HC154) is used to turn ON/OFF 16 SPMs and is controlled using digital input output pins of DSP which is shown in **Figure 4-8**. Two SPM modules are controlled using PWM pins of DSP which has been implemented for fine tuning of the output voltage and also for the regulation and controls. For rest of SPMs, digital output is used to control switch-on and switch-off according to the required set voltage. The controller can turn off all the SPMs quickly in case of any faults occurs such as dc over current or crowbar. Individual SPM is protected against internal faults, i.e. IGBT short circuit, over temperature and over current. The power supply can be either operated remotely using graphical user interface (GUI) or from local panel.

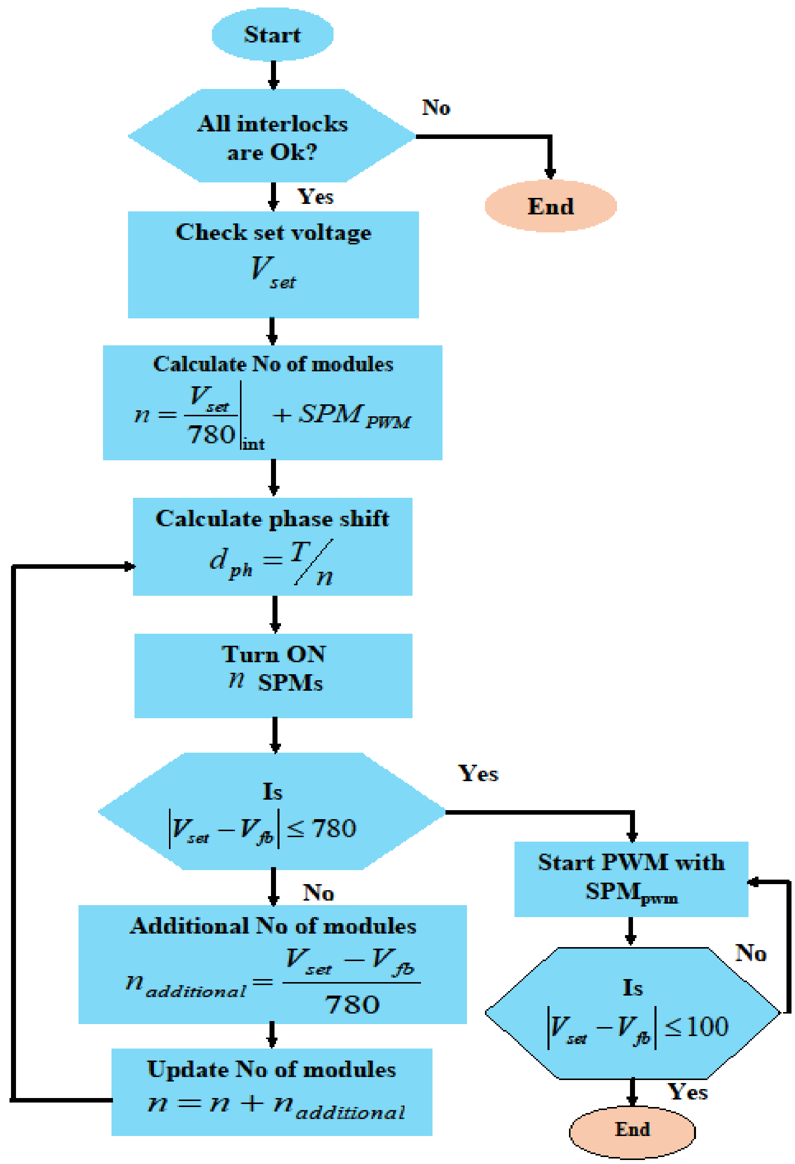


Figure 4-9: Flow diagram of control architecture

The DSP is used as an independent master controller without slave controllers which is a simpler design. The DSP based controller has many advantages like flexibility, accurate, not much affected by the noise, reconfigurable without much change in hardware etc. The only drawback is slow speed which requires few more ms time to achieve the desired set value, which in our case is not the serious issue.

The control architecture is based on the flow diagram which is shown in **Figure 4-9**. Flow diagram starts checking all the interlocks and then it checks the set voltage V_{set}. Since the duty cycle is fixed at 80% to 100% and for a specific number of modules, phase shift (T_d) can be calculated. The number of SPMs to turn on is given by n= V_{set}/780. The fraction part of V_{set}/780 V is controlled by two vernier SPMs for regulation.

4.3.3 Supervisory control and monitoring

The supervisory control and monitoring system for all the power supplies including HVPS is developed in-house by using PLCs and is programmed using Simatic manager software provided by Siemens. Siemens S7-300 PLC is used which handles all the fields I/Os. It takes care of all safety interlocks like over voltage, over current, water flow, air flow etc. along with the start-up interlocks. Auxiliary power supplies, at high voltage deck,

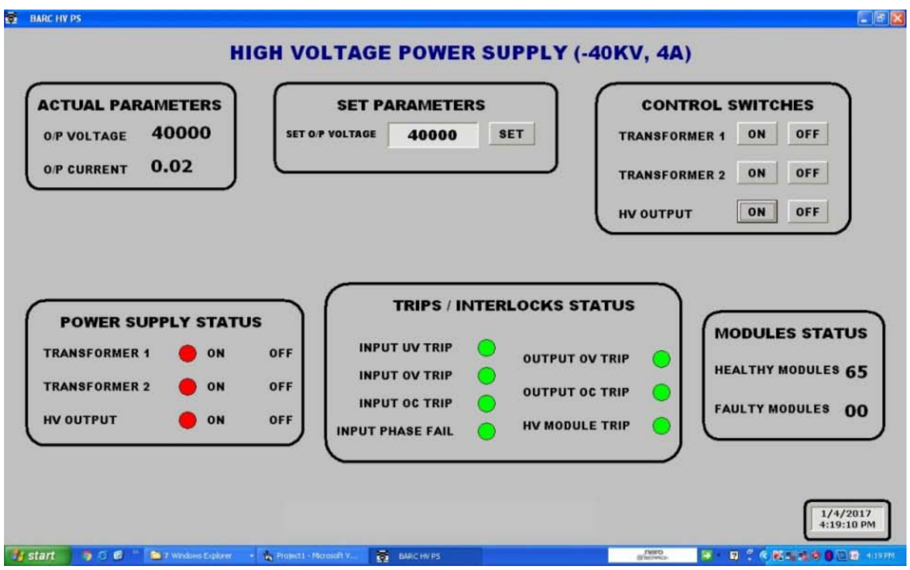


Figure 4-10: HVPS control and monitor GUI.

are controlled by Siemens distributed I/O modules (ET-200) with Ethernet. An Ethernet to optical and optical to Ethernet channel is used to navigate the control signals from high voltage deck to PLC. A GUI as a control panel is developed to control the HVPS from PC, as shown in **Figure 4-10,** along with control and monitoring of parameters of other systems also. From this panel, all the operations can be done related to the HVPS from remote PC.

4.4 Results and discussion

Both the resin cast transformers were fabricated and tested at factory. Results of all major tests, such as turns ratio test, polarity test, magnetic balance test, IR test, Insulation test at 80 kV (between all secondary shorted to HV with respect to primary coils & screen & core at ground) and DVDF test (double voltage at double frequency) were found to be satisfactory and meeting all the design specifications.

A test stand was made for functionality test and full load test of each SPM at 580 V, 3-ph, 50 Hz as input power. Heat run test was performed on randomly selected 25% of modules at full current and maximum temperature of power components was measured to be less than 73°C at an ambient of 25°C which is within the safe limit. After assembly, the HVPS was tested at full voltage at 40 kV dc and rise time and fall time are recorded up to 3A, i.e. 120 kW power for short time due to availability of load.

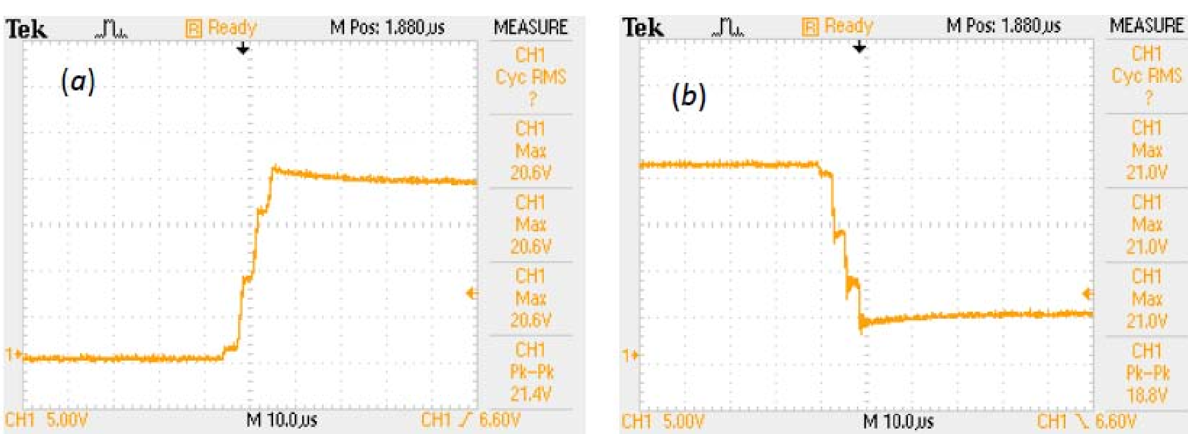


Figure 4-11: (a) Rise time and (b) fall time of output voltage (Y-axis at 10 kV/div) at 40kV at no load. X-axis indicates Time scale at 10 µs/div.

The rise time and fall time of HVPS were recorded and shown in **Figure 4-11** which is around 15 μs at no load. The available resistive load of 40 kW was used to test the power supply at higher current for short time. The line as well as load regulation of HVPS was tested at resistive load and found to be better than 0.5%. The over current protection at different current level adjustable from 3.0 A to 6.0 A was performed successfully at lower voltage.

The power supply as well as rf amplifier tube must be protected against crowbar or short-circuit caused due to internal arcing. To demonstrate low energy dump (<30 J) to the load during a fault, wire burn test was performed. For this purpose, a crowbar test set-up was connected across the output terminals. The test setup consists of a high voltage relay in series with a piece of a thin 33 SWG copper wire of 140 mm long suitable for 30 J of energy transfer. The result of crowbar test of HVPS performed at -25 kV is shown in **Figure 4-12**. The short circuit current was measured using a LEM CT and a current probe.

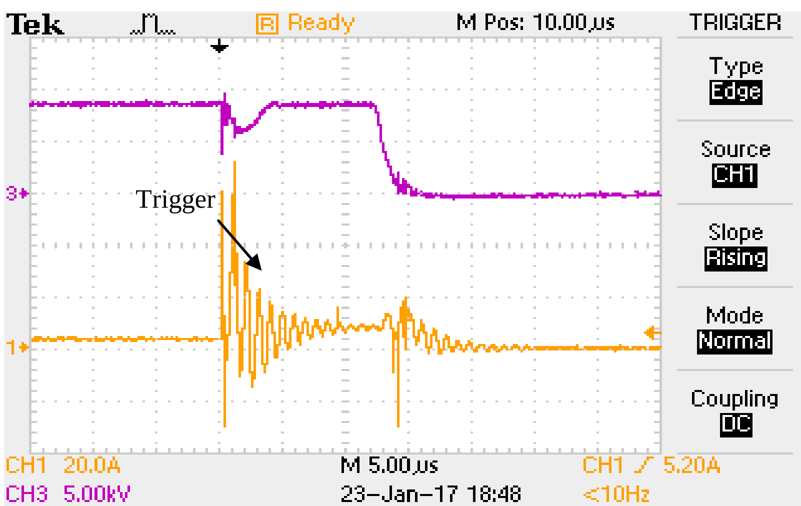


Figure 4-12: Short circuit test (CH3: voltage 15 kV/div which is scaled down to 3:1 by using voltage divider; CH1: current, 20 A/div)

To perform the crowbar test, a fault condition was generated by closing a high voltage relay in series with a piece of 33 SWG thin copper wire which is connected across the output terminals. Once the fault is sensed by a Person CT, the signal is fed to the controller which is fast enough to send the switch-off command to all the IGBTs in all SPMs. In **Figure 4-12**, It can be seen that within 15 μs, the power supply gets complete off without burning the thin copper wire. The tests were repeated and similar results were found. The HVPS efficiency is calculated to be better than 96.5% which is very good.

Transformer Loss = 2750 W , Losses in each module = 42 W @ 5 A

Total loss in 50 modules = 42x50 = 2100 W, maximum 50 modules gives required voltage.

Losses in other components = 1550 W, Total Losses = 2750 + 2100 + 1550 = 6400 W,

Thus, Efficiency = 200/(200+6.4) = 96.5 %.

4.5 Summary and conclusion

The HVPS has been developed, installed and tested with available resistive load up to 120 kW power level for a short time. Due to unavailability of services of IOT, the actual load installation will take some more time. Individually, all the modules are tested at full load and found to be compliant and meeting all the specifications. The HVPS is found to deliver excellent operating performances with inherent redundancy, faster dynamic response better than 15 μs, low stored energy which is less than 50 J and improved efficiency which is calculated to be 96.5%. Overall HVPS testing was carried out up to 40 kV at 3 A current (not exceeding 120 kW) for a short time and full current at -25 kV. This is due to the available resistive load. After the IOT installation and commissioning along with water cooling and other services, the rf testing will be done.

CHAPTER 5

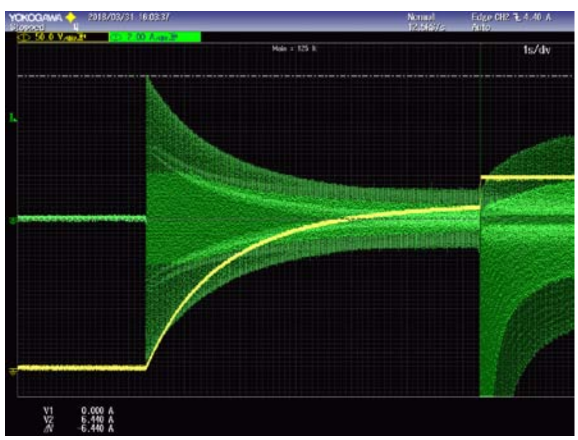
Study on harmonics and EMI

5.1 Introduction

The high voltage power supply (HVPS) based on pulse step modulation (PSM) technology (described in Chapter-4) has been widely used for various applications, ie., rf amplifiers, Electron Cyclotron Resonance Heating (ECRH) systems etc. The HVPS is a complex system which contains multi-secondary transformers followed by numbers of rectification units and switching converters modules. In such situation, there is huge scope of harmonics generation in the power system mainly due to non-linear behaviour of active and passive devices. In order to reduce the effects of harmonics, several corrective steps have been implemented. Heavy magnetic inrush current of the transformer and capacitor charging may trigger the overcurrent for the mains breaker.

Y-axis:- Ch-1 Voltage (yellow) 0 to 620 V dc.

Ch-2- AC Current (Green) -40 A to +40 A.



X-axis:- Time 1s/div

Figure 5-1: A typical soft charging at 440V (CH1- dc link voltage (yellow) from 0V to 620 Vdc, CH2- Input AC current (green) envelop which shows soft start condition of a transformer showing the soft charging of capacitor filter in time interval of 6s.

Sudden inflow of huge inrush current during start causes huge EMI and can disturb the surrounding equipment. For the protection of breaker and capacitors from overcurrent as well as the disturbances to other equipment resulting from EMI, a soft start procedure is necessary [46]. A typical soft start procedure of a module is shown in **Figure 5-1** which describes the flow of magnetising current as well as capacitor charging current slowly at the time of start. This helps to reduce EMI to great extent. PSM power supply starts up in two steps: soft start of transformer as well as each switched power modules. Considering the transient behaviour of soft start procedure, the resistors should be suitably selected which should balance the current decay time without any oscillation. Optimum resistor value (R) in series is calculated considering the equation

$R^2C^2 - 4\,LC > 0$,

So, $R > 2\sqrt{\frac{L}{C}}$, where L and C is circuit inductance and capacitance.

5.2 Study on Harmonics and their analysis

Each switched power module (SPM) consists of a 3-ph bridge rectifier followed by IGBT based buck converter. In a 6 pulse rectifier configuration, [47] the input current waveform will contain some harmonics and due to that the input current waveform looks as shown in **Figure 5-2**. The input current contains harmonics: **h = kq ±1**, where **h** is the harmonic number (integer multiple of the fundamental), **k** is any positive integer and **q** is the pulse number of the converter. This means that a 6-pulse (or 3-phase bridge configuration) rectifier will exhibit harmonics at the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th etc. multiples of the fundamental. As a thumb rule, the magnitudes of the harmonic currents is the fundamental current divided by the harmonic number (e.g. the magnitude of the 5^{th} harmonic would be about 1/5th of the fundamental current). A 12-pulse (or 6-phase rectifier) will, in theory, produce harmonic currents at the 11th, 13th, 23rd, 25th, etc. multiples. In reality, a small amount of the 5th, 7th, 17th and 19th harmonics will also be present with a 12-pulse system (typically the magnitudes will be on the order of about 10% of those for a 6-pulse drive) [47].

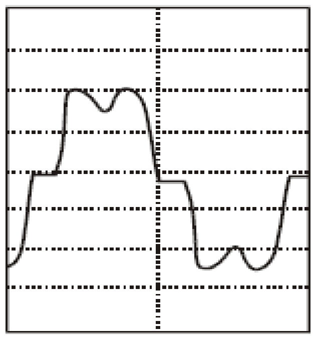


Figure 5-2: Input line current distorted waveform which contains harmonics.

Zero sequence harmonics (3rd, 6th, 9th, ….. (6n-3) th) do not produce a rotating field [48]. These harmonics circulate between the phase and neutral or ground. The third order or zero sequence harmonics, unlike positive and negative sequence harmonic currents, do not cancel but add up arithmetically at the neutral bus. Another set of special harmonics called "triplens" (multiple of three) which have a zero rotational sequence. ***Triplens*** are the odd multiples of the third harmonic (3, 9, 15, 21……). These harmonics flow in grounded star connected system and circulate in delta-connected windings which produce overheating. Positive sequence and Zero sequence harmonics are responsible for overheating of conductors, whereas Negative sequence harmonics, on the other hand, circulate between the phases creating additional problems as it rotates in opposite phasor rotation and produces more core loss [49].

We know that non-sinusoidal periodic complex waveforms are thus generated by adding together sinusoidal harmonics waveforms at the frequencies multiple of fundamental frequency which is shown in **Figure** 5-3 or vice versa. Harmonics are shown as multiples of the fundamental frequency (f), such as: $2f$, $3f$, $4f$, etc. Harmonics is generalised term used to describe the distortion in a sinusoidal fundamental waveform [47]. A complex and distorted periodic waveform can be split up mathematically into its individual components of harmonics by using Fourier Analysis Method.

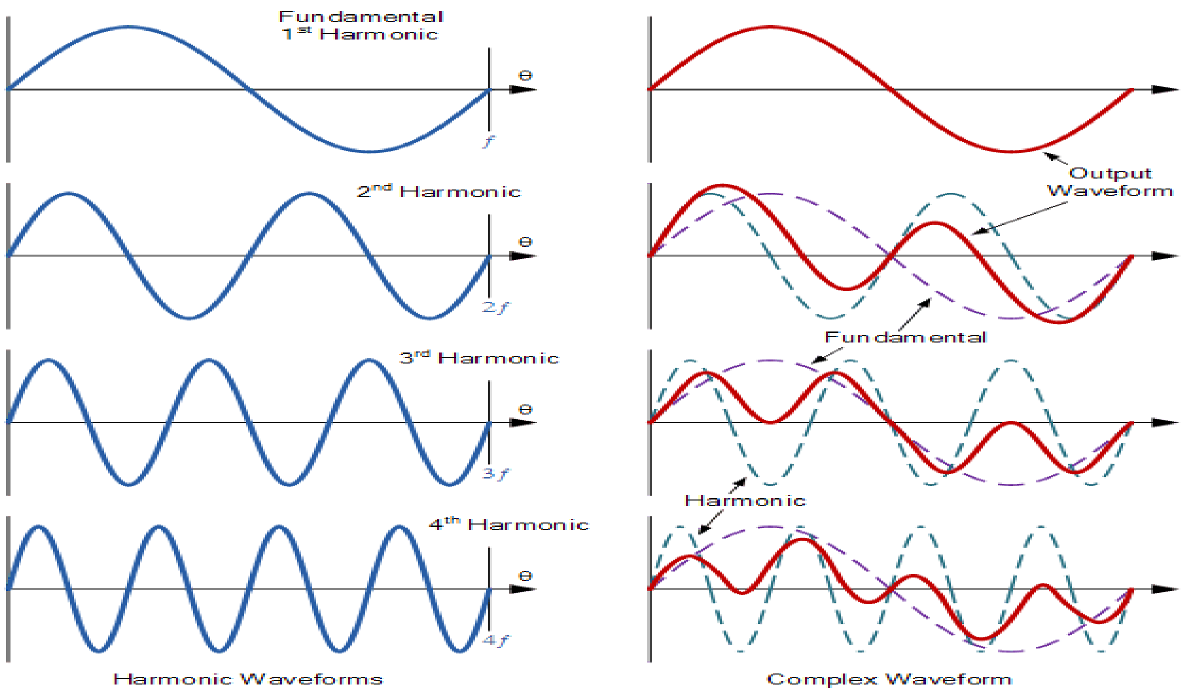


Figure 5-3: Complex waveform formed by adding the waveforms of several frequencies.

The amount of waveform distortion of a complex waveform and its distinctive shape is directly related to the frequencies and magnitudes of the most dominant harmonic components. The most dominant harmonic components are the low order harmonics from 2^{nd} to the 19^{th} with the triplens being the worst. The equation given for the value of a complex waveform will be:

$E_T = E_1 + E_2 + E_3 + \dots\dots\dots + E_{(n)}$

$E_T = V_{1max}\sin(\omega t) + V_{2max}\sin(2\omega t) + V_{3max}\sin(3\omega t) + \dots\dots + V_{nmax}\sin(n\omega t)$

Harmonic sequence refers to the phasor rotation of the harmonic voltages and currents with respect to the fundamental waveform. Normally, the amplitudes of harmonics is the ratio of fundamental amplitude divided by the harmonics number. If fundamental amplitude is A, 2nd harmonics amplitude = A/2, 3rd harmonics amplitude = A/3 and so on.

5.2.1 Fourier series

For a periodic function *f*(*x*) that is integrable on [−π, π], the number, the function can be represented as a sum as follows

$$S_N f(x) = \frac{a_0}{2} + \sum_{n=1}^{N} [a_n.\cos(nx) + b_n.\sin(nx)],\, N \ge 0$$

Where a_0 , a_n and b_n are called the Fourier coefficients of *function f(x)* which can be expressed as

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{+\pi} f(x)dx,\, n \ge 0$$

$$a_n = \frac{1}{\pi}\int_{-\pi}^{+\pi} f(x)\cos(nx)dx,\, n \ge 0$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{+\pi} f(x)\sin(nx)dx,\, n \ge 0$$

The partial sums for *f* are Trigonometric Polynomials. Since, the functions $S_N f(x)$ approximate the function *f(x)*, and that the approximation improves as $N \to \infty$ Infinite Series. $S_N f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(nx) + b_n \sin(nx)$

is called the **Fourier series** of *f(x)*. These trigonometric functions can themselves be expanded, using multiple angle formulae.

The most commonly-used measure for harmonics is total harmonic distortion (THD), also known as distortion factor. It is applied to both voltage and current. THD is defined as the rms value of the harmonics above fundamental, divided by the rms value of the fundamental. THD of a voltage or current can be defined as

$$THD_F = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \text{.........}}}{V_1}$$

where V_n is the RMS voltage of n th harmonic and $n = 1$ is the fundamental frequency.

5.2.2 Harmonics reduction by transformer configuration

The PSM based high voltage power supply (-40kV, 5A) consists of two multi secondary transformers. First one transformer, primary is Y connected and secondary windings are Y connected and in second transformer, primary in Δ and secondary windings are in Y connected. Thus all secondaries are star connected which served in parallel connection to give output 12 pulse rectification, as shown in **Figure** 5-4. Line-to-line transformer voltage ratios are identical for all secondary windings. The top transformer is in Y-Y connection thus having no phase shift. The transformer in bottom has Δ-Y, thus having 30° phase shift. Finally, the secondary currents of both the transformers operate in parallel provide 12 pulse rectification and thus the THD is reduced considerably around 1.25%. Hence, 12 pulse rectification automatically reduces the filter size.

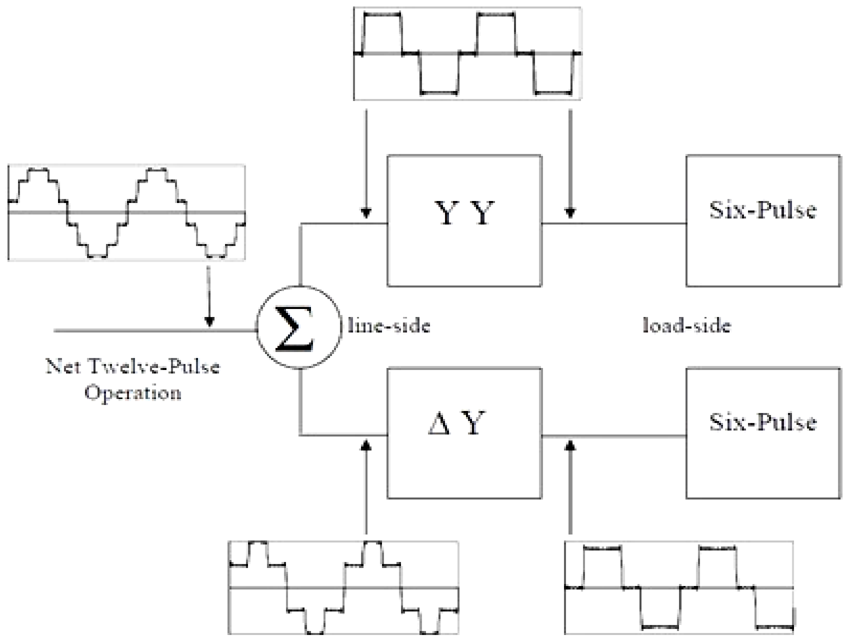


Figure 5-4: Primary transformer connection and analysis of transformers

Assuming the balanced load, each 3-phase secondary undergo 6 pulse rectifications as shown in Fig-2. From Fourier transformation, it can be seen that being a half wave symmetry, even-ordered harmonics will remain absent [47, 50, 51]. So, resultant current can be written as $\boldsymbol{I_{net}(t) = 2I_1 \sin(\omega t) + \frac{2I_1}{11}\sin(11\omega t) + \frac{2I_1}{13}\sin(13\omega t) + \ldots\ldots\ldots\ldots}$

Recognizing the pattern shows that the remaining harmonics are **h = 12n ±1 ,** whereas n=1,2,3…. which leads to the classification “twelve-pulse converter” and this way harmonics content in input current is reduced to almost half of 6-pulse converter and hence THD can be improved by using 2 transformers in 12 pulse converter mode. The presence of harmonics may affect the systems in following way-

a) Skin effect due to higher frequencies and also results more loss.

b) Triplen harmonics circulating in neutral conductor making excessive heating.

c) Negative sequence produces opposite rotating field which reduces flux linkage.

5.2.3 Harmonics standards

For harmonics generation, the system design must have compliance. One of the major standards is International Electro technical Commission (IEC) European Standards where EN 61000-3-2 Harmonic Emissions standard is applied to household appliances. There are four classes Class-A, B, C and D for various purposes. Additional harmonic current testing, measurement techniques and instrumentation guidelines for these standards are covered in IEC 1000-4-7 [48].

5.3 Study on EMI and EMC

Electromagnetic interference (EMI) is an unwanted electromagnetic disturbance that interrupts, obstructs or otherwise degrades the equipment performances which is a major concern for all the electrical and electronics systems. The sources of EMI have been commonly identified as the equipment or system incorporating very high rate of switching voltage or current (dv/dt and di/dt) interacting with parasitic components. EMI produces two types of emissions; conducted (voltages or currents) and radiated (electric or magnetic fields in range of few MHz or more). Typically Switch-Mode Power Supplies produce conducted interference signal (operating in the range of 10 kHz to 100 kHz). For EMI to exist there must have an electrical noise (EMI) source, a coupling path, and a victim receptor. Four different types of elementary EMI coupling can be identified: Impedance coupling, Inductive coupling, capacitive coupling and radiative coupling [52, 53]. The dominant disturbing phenomena are due to the inductive coupling, followed by capacitive and impedance coupling, which are relatively more prominent with the increase in frequency. At much higher frequencies, generally the field strength of radiative coupling increases the susceptibility limit to cause EMI phenomena.

There are several ways for the comparative study of the spectral characteristics of random-switching schemes that apply to the basic pulse width-modulation (PWM) dc/dc converters operating in discontinuous conduction mode (DCM) [54, 55]. Mathematical modeling was done and low frequency harmonics analysis and random noise calculation was done experimentally also. The Buck converter exhibits a complex nonlinear behaviour and produces EMI at switching frequency and harmonics. Various methods have been studied to reduce noise emission by the power supply which uses frequency modulation and finally, a novel voltage feedback method is discussed to make the converter working on chaotic state to improve EMI and reduce output ripple [55-57].

A receptor, also called a "victim", is exposed to a conducted or radiated electromagnetic energy which shows degradation or malfunction in performance. Hence, receptors are designed in such a way which can withstand the limit of EMI without malfunction. Thus the components must comply with specifications to ensure electromagnetic compatibility (EMC) which represents the ability of systems to function as designed, without malfunction or unacceptable degradation of performance due to EMI within their operational environment. During the development of a system, the product must be designed to comply with EMC standards, and the product must also be tested for EMC [58, 59]. The conducted EMI noise in a PWM inverter consists of two parts, differential mode (DM) noise and common mode (CM) noise, whose details and noise current flow direction are illustrated in **Figure 5-5**.

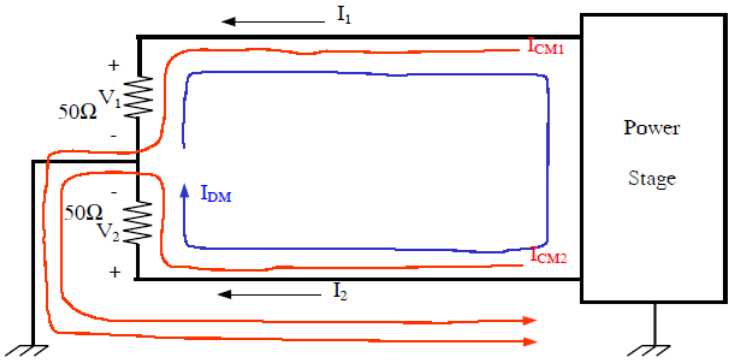


Figure 5-5: Common Mode (CM) and Differential Mode (DM) current

The common mode (CM) noise is generated mainly due to the high rate of change of voltage (*dv*/*dt*) caused by the switch turn on/turn off, coupled through the parasitic capacitance between the IGBT collector and the module base-plate heat sink that is normally grounded. The CM noise current flows through both the input lines into the ground through the stray capacitance. The differential-mode (DM) noise current (I_{DM}) is largely due to di/dt in the dc bus as the normal switching operation of the converter and flows between the phase and neutral lines.

In order to mitigate the effect of EMI, there are various schemes ie., use of EMI filter, short & twisted cable pair of smaller length which reduces parasitic inductor and capacitors, snuber circuit etc [59]. Sharp rising edge and falling edges will have more dv/dt and causes CM noise. Snuber capacitor is used to limit the IGBT turn-off dv/dt. As the EMI generation is unpredictable [53, 60] and so it needs perfect design, modelling, simulation and noise spectrum estimation. The most common method is Fast Fourier Transform (FFT) to get a wide-band varying EMI-spectrum and information of power spectral density verses problematic harmonic frequencies.

5.3.1 EMI characterisation

The continuously growing market demands for fast-switching power supplies and giving rise to the need of more controlled methodologies to meet regulatory electromagnetic compliance (EMC) requirements [60-62]. The resonant converters type switching mode power supplies (SMPS) are in use implementing zero-current (ZCS) or zero-voltage (ZVS) operation which minimizes switching losses and noise. Also, the conducted and radiated noises emitted from SMPS making the need of proper input filter design which is also an intricate part of the overall power supply design. EMI can be in the form of conduction or radiation [63]. Conducted EMI passes through supply lines and interconnecting wires and is divided into Common Mode (CM) and Differential Mode (DM). Differential mode follows the same path as the input power while the common mode has a current path through earth (chassis). Common-mode (CM) emissions are generally due to the rapid switching of voltage across parasitic capacitances [64].

General topology of the input filter section of power supply for suppression of EMI noise is as shown in **Figure 5-6**. In the diagram, Cy elements represent Y-Capacitor values

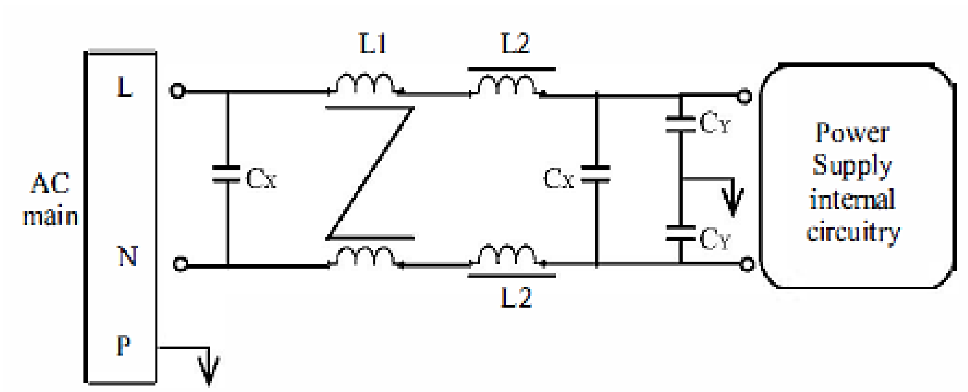


Figure 5-6: EMI filter between switched power module and mains supply

which is chosen to effectively shunt common mode currents from reaching the power supply. Capacitor Cx elements are X-Capacitors used to control differential mode harmonics [65, 66]

Inductor L1 is used with a purpose of further suppressing high frequency CM noise currents while inductors L2 limits deferential modes by utilizing the leakage capacitance resulting from the proximity of windings from one another. The filter also serves the essential purpose of preventing noise fluctuations from AC input signal to the power supply. When designing to meet regulatory emission standards, proper attenuation of the noise requires an adequate number of filter stages. There may have Single-section or multiple sections of EMI filters with careful attention to the parasitic. While choosing a capacitor, the effect of ESR and ESL is very important which affect the resonant frequency. Electromagnetic interference (EMI) filters have been used for power electronics converters to attenuate switching noise to meet the EMI standards. However, because of the parasitic in the filters, it cannot attenuate high-frequency noises efficiently. There are few techniques to mitigate the effects [58, 67-69].

There is no setup available at present in our lab for the measurement of conducted EMI, but some labs have this facility for the measurement of noise. Line Impedance Stabilization network (LISN) is one of the most common part whose schematic is shown in **Figure 5-8** to measure the conducted noise emission which propagates from the device back into electrical power system [59]. LISN provides specified measuring impedance for noise and isolates the DUT. **Figure 5-7** shows a typical graph which shows the harmonics reduction by using a filter measured by LISN and network analyser.

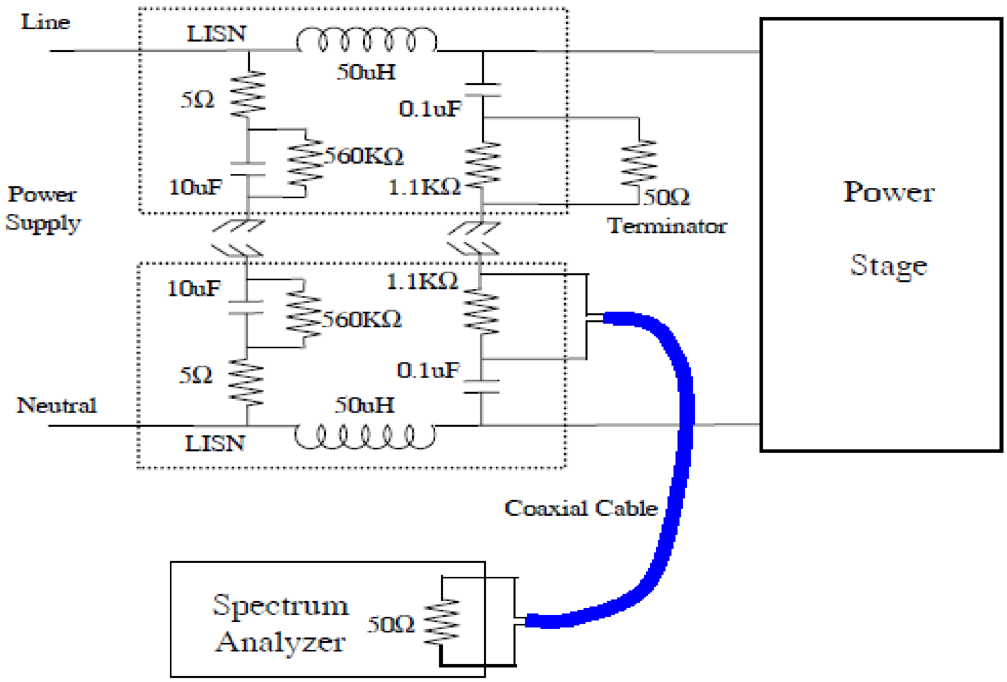


Figure 5-8: Arrangement of conducted noise measurement by using LISN

The noise voltage measurement is made at the plug end of the inverter power cord and is expressed as the voltage developed across the 50-Ω port terminated by using spectrum analyser terminated with 50-Ω inside. A test bench can be made consisting of noise source, device under test, LISN and measuring instruments. Various combinations of result and EMI spectra can be taken for its analysis and characterization [59].

5.3.2 EMC standards

The objective of EMC standards is to ensure reasonable electromagnetic compatibility for trouble-free co-existence by limiting emission of EMI and ensuring that these systems have adequate level of immunity to EMI generated in the vicinity by other equipment [70-73]. EMC standards can be broadly classified into Military and Civilian standards. Most of the military standards are broadly for military applications for land based, air borne or ship borne equipment based on MIL STD 461 & 462 evolved by US Department of Defence (DOD). The Civilian Standards are for the equipment having non-military applications, i.e. for equipment used in commercial, industrial, domestic and automotive environments. Most of the civilian standards are based on organizations like CISPR, IEC, IEEE, SAE, SAMA etc. Most common CISPR standard has been referred to "International Special Committee for Radio Interference".

Some of the commonly referred CISPR standards are: [68]

a) CISPR 11: For Industrial, Scientific and Medical (ISM) equipment
b) CISPR 14: For household appliances, electric tools and similar apparatus.
c) CISPR 15: Limits and methods of measurement of radio disturbance characteristics of electrical lighting equipment.
d) CISPR 16-1 For radio disturbance and immunity measuring apparatus and methods

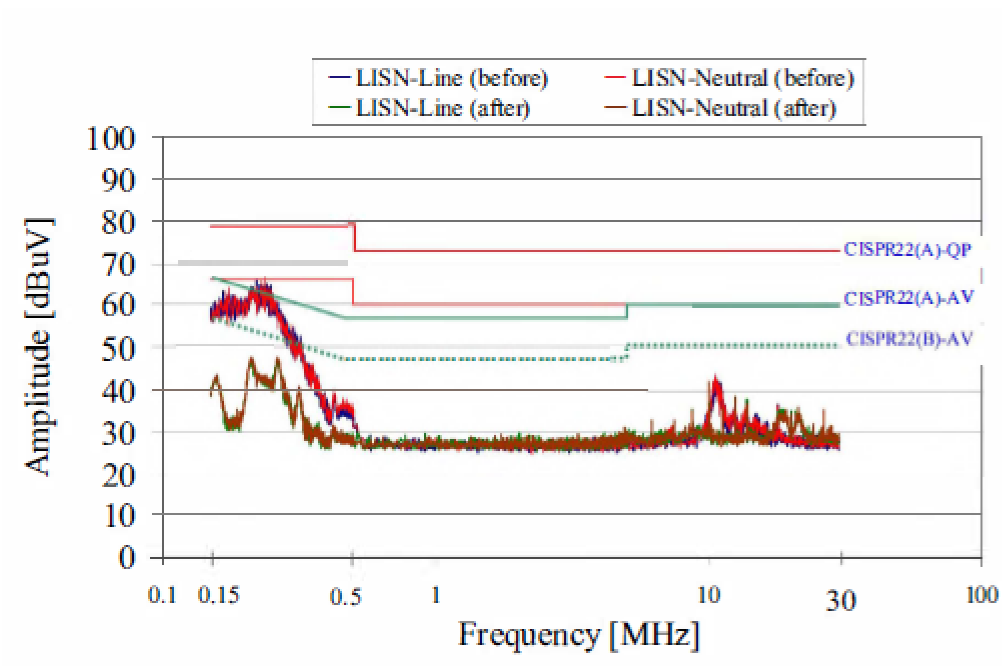


Figure 5-9: A typical noise curve whose amplitude is plotted in frequency band [67]

Some other most widely accepted commercial standards are Federal Communications Commission (FCC), British Standards (BS), Verband Deutscher Elektrotechniker (VDE), and Voluntary Control Council for Interference (VCCI). Also, international standards on electromagnetic compatibility such as EN (European Norm) and CISPR (International Special Committee on Radio Interference) become the guidelines for designers to reduce noise reduction in switching power supplies [63, 67].

CHAPTER 6

Conclusion and future works

6.1 Conclusion

The thesis has analyzed varieties of topologies on high voltage power converters and related systems. Complete design, circuit analysis, development and testing of all the high voltage power supplies have been carried out indigenously. Several high voltage power converters have been in operation, viz, 20 kV, 22.5 A and -30 kV, 3.2 A for the cyclotrons on round the clock basis. The power supply 20 kV, 22.5 A is used for anode of tetrode tube based rf amplifiers (three numbers) where output voltage regulation is optional. The output voltage setting from 10kV onwards is done by 400 kW oil cooled variac. Although the power supply has been performing very well but regular maintenance of oil cooled variac is required. Also, due to low frequency ripple at 600 Hz, larger value of filter capacitor of value 30 µF is worked out which amounts to 6.0 kJ stored energy. This necessitates the use of a high voltage ignitron as a crowbar switch to limit energy less than 50 J transferring to the tube during internal arcing. An ultrafast crowbar protection system is the most critical system required for the protection of costly tubes. Also, for proper functioning of the ignitron, the anode temperature must be kept 8-10°C higher than the cathode for mercury vapour condensation.

Another HVPS rated at -30 kV, 3.2 A is for the IOT cathode and so a negative polarity high voltage power supply. This power supply is primary phase controlled SCR regulated with the regulation better than 1%. In this case also, the ripple frequency is at 600Hz which is very low and resulting higher filter capacitor and higher stored energy.

Similarly, crowbar protection system has to be incorporated by using an ignitron of rating 50 kV. Because of the negative polarity of HVPS, the ignitron cathode has to be kept at high voltage at -30 kV with grounded anode and due to that whole circuitry including triggering circuit and pulse transformer are to be kept floating at high voltage. Thus, the crowbar protection has become much complicated and online testing is much more difficult. This is to be noted that during crowbar fault, sometime the components failure was observed in SCR firing card. After several iterations, transient voltage suppressors were put suitably and observed the significant improvements.

Conventional power supplies have some inherent disadvantages which have been rectified to great extent in newly developed high voltage power supply based on PSM topology. Various journals and publications were studied on PSM based topology and after extensive survey; a final scheme was worked out for high voltage power supply. After going through several iterations of modifications, first of all, a prototype of smaller rating power supply was designed, simulated and developed by using 4 modules and tested thoroughly. A DSP based controller was also designed and developed suitable to PSM based HVPS after several iterations. Then, -40 kV, 5 A high voltage power supply based on PSM based technology has been taken up utilizing a new and improved design with modular construction. It's a fully computer controlled system and a user's friendly GUI is developed for control and parameters readout. This was completely new development and required lots of study and literature survey which itself is a field of intense R&D.

The HVPS was tested thoroughly and performances were found satisfactory as per our required specifications. Voltage regulation was checked at resistive load. Voltage regulation is found to be better than 0.5% for load change from 10% to 90%. The HVPS efficiency is calculated to be better than 96.5%. Also, it possess very fast response ie, less than 15ms which is enough to perform crowbar function without the use of any fast operating switch, ie ignitron etc. The design reports along with the theoretical analysis would be very helpful and novel idea for the future maintenance and up gradation works. Optimization of the physical size issue has to be worked on in next phase.

6.2 Future works

This dissertation has been dedicated towards the development of high voltage systems (-40 kV, 5 A) as per load requirements point of view. Lots of R&Ds were done for the development of PSM based HVPS to match our requirements. There are still some scope for the further improvement for the PSM based HVPS for better results and performances. The sizes of multi secondary transformers and SPMs became little large which will be taken care of. The resin cast multi secondary transformer has been made overrated as its behavior was not certain. It was later felt that the multi-secondary transformer of smaller size can improve its performance due to smaller inductance and capacitance between the coils. Optimization of the physical size issue has to be worked on in next phase which will be helpful to achieve more improved performances.

In next phase, all the conventional high voltage power supplies will be replaced by the PSM based power supply with improved performance.

Bibliography

[1] Abraham I. Pressman on “Switching and Linear Power Supply Power Converter design” published by Hayden Book Co. in Rochelle Park, N.J, 1977.

[2] Josna Ann Joseph, S. Bella Rose, “A High Efficiency ZCS-ZVS Buck Converter with Coupled Inductor” International Journal for Research and Development in Engineering (IJRDE), 2014, ISSN: 2279-0500, pp- 053-058

[3] Kuo-Kuang Chen, “A Novel Application of Zero-Current-Switching Quasi resonant Buck Converter for Battery Chargers” Hindawi Publishing Corporation Mathematical Problems in Engineering, Volume 2011, Article ID 481208, 2011.

[4] Jose Bostos “DC-DC Switch Mode Converters”, Chapter-7, by John Willay & Sons Inc., 2008.

[5] S. K. Thakur, T. P. Tiwari, J. S. Prasad, A. De, Y. Kumar, S. Som, S. Saha, R.K. Bhandari “Development of power supplies for 3-ф, 240 kw rf system with crowbar protection for superconducting cyclotron at VECC” Proceedings of CYCLOTRONS 2010, Lanzhou, China, pp.- 60-62.

[6] S. K. Thakur, “Design and performance of high voltage power supply with crowbar protection for 3-Φ high power rf amplifier system of cyclotron”. Journal of Instrumentation (JINST 11 T07004), vol.-11, 2016.

[7] S. K. Thakur, Y. Kumar, “Design development and testing of high voltage power supply with crowbar protection for IOT based RF amplifier system in VECC”. Journal of Instrumentation (JINST 13 T05009), vol.–13, 2018.

[8] S. K. Thakur, S. K. Kumari, Yashwant Kumar, “Design and performance analysis of a crowbar-less high voltage power supply based on PSM technique”, Sadhana, vol-43, Issue 8, 2018, pp 1-9/129. https://www.ias.ac.in/article/fulltext/sadh/043/08/0129.

[9] S. Som, S. Seth, A. Mandal, S. Paul, A. Duttagupta, “Radio frequency cavity analysis, measurement, and calibration of absolute Dee voltage for K-500 superconducting cyclotron at VECC, Kolkata”, Review of Scientific Instruments **84**, 023303, 2013.

[10] M. Acharya, J. V. S. Hari Krishna, A.C. Suthar, “Analysis of Tetrode amplifier”, JETIR, Vol-2, 2015, pp- 2096-2099.

[11] D. Bora, S. Dani, S. Gangopadhyay, B. Jadav, M. Jha, “High power continuous wave microwave system at 3.7 GHz”, Review of Scientific Instruments **72 1869,** 2001. http://link.aip.org/link/doi/10.1063/1.1347373

[12] Eimac Tetrode Tubes data sheet,. http://www.cpii.com/search.cfm, May, 1983

[13] S. G. E. Pronko, T. E. Harris, “A New Crowbar System for the Protection of High Power Gridded Tubes and Microwave Devices”. IEEE International Vacuum Electronics Conf., The Netherlands, 2001.

[14] J. W. Robinson, “Self-crowbarring, load-isolating triggered spark gap”, Review of Scientific Instruments **51 1532**, 1980.

[15] A. K. Mitra, “Measurements of crowbar performance of the 20 kV 130 A DC power supply of the TRIUMF RF system”, Proceedings of Particle Accelerator Conference, San Franscisco, USA, 1991, pp- 938-939.

[16] A.K. Mitra, P.J. Tallerico, “Spark-Gap Crowbar for High-Voltage Power Supply”, IEEE Trans. Nucl. Sci., 30(4),1983, pp- 2862.

[17] M. Kushwah, B. Pal, Y. S. S. Srinivas, D. Bora, “Anode modulator power supplies for continuous duty 500 KW klystrons (TH2103D) & 200KW Gyrotron (VGA8000A19)”, IEEE symposium of Fusion Engineering 2002, Atlantic City, NJ. pp 84.

[18] M. K. Badapanda, A Tripathi, R Upadhyay, M. Lad, P. R. Hannurkar, “High-Power RF Testing of 1-MW, 352.2-MHz Continuous Wave Klystron Amplifier”, IEEE Trans. on Plasma Science. 43 (10), 2015, pp. 3599.

[19] A.Y. Wu, M. D. Driga, H. H. Woodson, R. C. Zowarka, “Simulation and predicted performance of the balcones gedi experiment”, IEEE Transactions on Magnetics, 22 (6), 1986, pp. 18-17.

[20] Data sheets Richardson Electronics application notes for Ignitron mounting and maintenance. https://www.relltubes.com/filebase/en/src/Datasheets/NL7703EHV.pdf.

[21] Data sheets of ignitron NL7703EHV, Richardson Electronics. https://www.relltubes.com/filebase/en/src/Datasheets/NL7703EHV.pdf

[22] Meenu Kaushik, L. M. Joshi, “Inductive output tube (IOT) – a review”, Journal of Electromagnetic Waves and Applications, 2015, pp- 2027-2037.

[23] R. G. Carter, “Acceleration technologies for charged particles: an introduction”, Contemporary Physics 52, vol-15, 2011.

[24] Kaushik M, L. M. Joshi, “Inductive output tube: a promising microwave source for high power applications”, International Journal of Electronics and Communications Technology (IJECT), 2015; 6:182–184.

[25] M. B. Shrader, D. H. Priest, R. N. Tornoe, “High power CW klystrode amplifier for 267 MHz”, Particle Accelerator Conference of IEEE-1993. Vol. 2; Washington, DC; 1993, pp-1103–1105.

[26] Yates C., Li Y., McCune E. W., “Performance characteristics of an MSDC IOT Amplifier”, IEEE Transactions on Electron Devices. 2001; 48:116–121.

[27] Wheelhouse A., Sobieradzki E., “1.3 GHz inductive output tube for particle accelerators”, Particle Accelerator Conference 2005; Knoxville; 2005. pp 3883–3885.

[28] S. Som, A. Mondal, S. Ghosh, S. Seth, S. K. Manna, S. K. Thakur, S. Saha, U. S. Panda, “Development and energisation of IOT based RF amplifier”, Indian Particle Accelerator Conference (InPAC-2013), Kolkata, India, 2013, pp-472-474.

[29] Y. Srinivas, M. Kushwah, S. Kulkarni, "Results of 10-Joule wire-burn test performed on 70kV rail-gap crowbar protection system for high power klystrons and Gyrotron," 19th Symposium on Fusion Engineering, 2002, pp. 91-94.

[30] Alex J., Schminke W., “Fast switching modular high voltage DC/AC power supplies for RF amplifiers and other applications”, In: Proceedings of 16th IEEE/NPSS SOFE vol. 2, 1995, pp. 936–939.

[31] Schminke W., “High-power Pulse-Step Modulator for 500 kW Short-Wave and 600 kW Medium-Wave Transmitters”, Brown Boveri Rev. 73, 1985, pp. 235-240.

[32] Schminke W., “The Development of Plasma-heating Equipment and Classical High-Power Broadcast Transmitter Technology”, Fusion Technology 1988, pp 432-437.

[33] Zhang J., Hao Xu, Wei W., Huang Y., “The Design of PSM-Based ECRH Power Supply Control System”, Journal of Power and Energy Engineering, vol. 4, 2016, pp 91-102.

[34] S. M. Pan, P. Fu, L. Yang, C. D. Hu, "The Control System of The 100kV HVPS For NBI", IEEE/NPSS, 24th Proc. of Symposium on Fusion Engineering 2011, SP3-34.

[35] Tomljenovic N., Schminke W., "Solid state dc power supplies for gyrotron and NBI sources", Proc. of Symposium on Fusion Technology, 1992, pp 952-956.

[36] N. P. Singh, U. K. Baruah, P. J. Patel, S. K. Mattoo and NBI Team, "Studies on the behaviour of multi-secondary transformers used for regulated HV power supplies", Fusion Engineering and Design, Volume 75-79, 2005, pp 127-133.

[37] V. Tripathi, N. P. Singh, L. N. Gupta, Kapil Oza, Paresh Patel, U. K. Baruah, "Development of Cast Resin Multi-secondary 1600kVA Transformer for Regulated High Voltage Power supply-A Prototype", 23rd National Symposium on Plasma Science & Technology (PLASMA-2008), vol-1, pp 40-46.

[38] P. J. Patel, P. K. Sharma, U. K. Baruah, "Regulated High-Voltage Power Supply (RHVPS): Integration, Operation and Test Results with LHCD System of SST-1", IEEE Transactions on plasma science, vol. 42, no. 3, 2014, pp. 651-655.

[39] A. Patel, H. Dhola, D. Upadhyay, B. Raval, K. Mehta, N. Goswami, N. P. Singh, A. Thakar, D. Parmar, S. Gajjar, R. Dave, V. Gupta, U. K. Baruah, S. Athaullah, Y. Dileep, A. Rajakiran, D. H. Rathod, N. Appa Rao, K. Mahadev, "Development of 3 MW dual output high voltage power supply for ICRH system". IEEE International Power Modulator and High Voltage Conference (IPMHVC) 2016, pp. 95 – 100.

[40] Jian Zhang, Xu Hao, Wei Wei, Yiyun Huang, "The Design of PSM-Based ECRH Power Supply Control System". Institute of Plasma Physics Chinese Academy of Sciences, Hefei, China, Journal of Power and Energy Engineering, 2016, vol. - 4, pp. 91-102, http://dx.doi.org/10.4236/jpee.2016. 44009.

[41] Amit Patel, Suryakant Gupta, N.P Singh, U.K. Baruah, "Power supplies for plasma heating: PSM and involved challenges". IEEE conference on "National Power Electronics Conference" (NPEC) at College of Engineering, Pune, India during December 18-20, 2017, Pages: 37 – 41.

[42] Lieying Yao, Yingqiao Wang, Xiaohui Mao, Yali Wang, Qing Liet, "A Fully Digital Controller of High-Voltage Power Supply for ECRH System on HL-2A", IEEE/NPSS 24TH Symposium on Fusion Engineering, 2011, pp 1-3.

[43] X. H. Mao, L. Y. Yao, Y. Q. Wang, Y. L Wang., Q. Li, M. Zhang, W. M. Xuan, "A Pulse Step Modulator High Voltage Power Supply for Auxiliary Heating System on the HL-2A Tokamak", IEEE transactions on Plasma Science, VOL. 42, NO. 12, 2014, pp. 1425-1429.

[44] M. K. Badapanda, A. Tripathi, R. Upadhyay, M. Lad, P. R. Hanurkar, "High-Power RF Testing of 1-MW, 352.2-MHz Continuous Wave Klystron Amplifier", IEEE transactions on Plasma Science, vol. 43, no. 10, 2015, pp. 3599-3607.

[45] TMS320F28335 Delfino Microcontroller. Available: http://www.ti.com/product/tms320f28335.

[46] L. L. Xia, M. Zhang, S. X. Ma, K. X. Yu, "Research of the Soft Start Circuit for the High Voltage Power Supply Based on PSM Technology" IEEE 25th Symposium on Fusion Engineering *(SOFE)*, San Francisco, CA, 2013, pp. 1-4.

[47] Mack Grady, "Understanding Power System Harmonics", Department of Electrical & Computer Engg., University of Texas, 2012, www.ece.utexas.edu/~grady .

[48] Stefanos Manias, "Harmonic treatment in industrial power systems", IEEE conference PESC-02, 2002.

[49] D. Zhao, J. A. Ferreira, H. Polinder, A. Roc'h, F.B.J. Leferink, "Investigation of EMI Noise Transfer Characteristic of Variable Speed Drive System" International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2006, pp S26 13-18.

[50] Robert G. Ellis, P. Eng., "Power System Harmonics a Reference Guide to Causes, Effects and Corrective Measures", published by Rockwell Automation in 2001, An Allen-Bradley series Report.literature.rockwellautomation.com/idc/groups/literature/.../wp/mvb-wp011_-en-p.pdf.

[51] C. P Steinmetz, "Theory and Calculation of Alternating Current Phenomena", McGraw-Hill, Inc., New York, 1916.

[52] Power Quality Application Guide on "Earthing a EMC Fundamentals of Electromagnetic Compatibility" Published by European Copper Development Institute, 2006, Belgiam.

[53] M. Kuisma, K. Rauma, P. Silventoinen, "Using Switching Function in Preliminary EMI analysis of a Switching Power Supply" IEEE 36th Power Electronics, 2005, pp 994-998.

[54] K. K. Tse, Henry Shu-hung Chung, S. Y. R. Hui, H. C. So" A Comparative Investigation on the Use of Random Modulation Schemes for DC/DC Converters" IEEE Transactions on industrial electronics, Vol. 47, NO. 2, 2000, pp- 253-263.

[55] Jeyanandh Paramesh, Annette von Jouanne, "Use of Sigma–Delta Modulation to Control EMI from Switch-Mode Power Supplies" IEEE transactions on industrial electronics, vol. 48, No. 1, 2001, pp 111-117.

[56] K. K. Tse, Raymond Wai-Man Ng, Henry Shu-Hung Chung, S. Y. Ron Hui, “An Evaluation of the Spectral Characteristics of Switching Converters With Chaotic Carrier-Frequency Modulation” IEEE Transactions on industrial electronics, vol. 50, no. 1, 2003, pp 171-182.

[57] Zhenjun Wu, Lifang Wang, “Research on Reducing EMI and Output Voltage ripple of Buck converter Based on a Novel Chaos Control” 7th International Conf. on System Simulation and Scientific Computing, 2008, pp 1031-1034.

[58] Krishna Mainali, Ramesh Oruganti, Student and Senior Member, IEEE, “Conducted EMI Mitigation Techniques for Switch-Mode Power Converters: A Survey” IEEE transactions on power electronics, vol. 25, no. 9, 2010. pp 2344-2356.

[59] Yuqing Tang, “High Power Inverter EMI characterization and Improvement Using Auxiliary Resonant Snubber Inverter. Virginia Polytechnic Institute and State University, Virginia, PhD Thesis, 1998.

[60] M. H. Nagrial, A. Hellany, “EMI/EMC Issues in Switch Mode Power Supplies (SMPS),” International Conference and Exhibition on Electromagnetic Compatibility, EMC York 99, 1999, pp 180 – 185.

[61] Eric Chikando, Samuel Connor, Bruce Archambeault, “Effects of 'Can' Filter on EMI Performance of Switching Power Supplies”, IEEE International symposium on electromagnetic compatibility, 2009, pp 36-40.

[62] Ned Mohan, Tore M. Undeland, William P. Robbins "Power Electronics: Converters, Applications and Design", John Wiley & Sons, Inc., New York, second edition, 1995.

[63] Mohamed Miloudi, Abdelber Bendaoud, Houcine Miloudi, Said Nemmich, Helima Slimani, “Analysis and Reduction of Common-Mode and Differential-Mode EMI

Noise in a Flyback Switch-Mode Power Supply (SMPS)", 20th Telecommunication Forum, TELFOR 2012, Belgrade, 2012, pp- 1080-1083.

[64] Khalid Zeineddine, Alexander Uan-Zo-li, Chung-hao Chen, Jaehong Hahn, Dong-ho Han, "A Power-Efficient Method to Mitigate the EMI of Switched-Mode Power Supplies", IEEE 8th International Conference on Power Electronics - ECCE Asia, Jeju, Korea, 2011, pp- 453-459.

[65] Qingbin Chen, Wei Chen, Qingliang Song, Yongfa Zhu, "An evaluation method of transformer behavior on common-mode conduction noise in SMPS" IEEE 9th International Conference on Power Electronics and Drive Systems-PEDS-2011, Singapore, pp - 782-786.

[66] Himanshu K. Patel, "Critical considerations for EMI filter design in switch mode power supply", IEEE International Conference on Industrial Technology (ICIT), 2006, pp 1843-1848.

[67] Shuo Wang, Rengang Chen, Jacobus Daniel Van Wyk, Fred. C. Lee, Willem Gerhardus Odendaal, "Developing Parasitic Cancellation Technologies to Improve EMI Filter Performance for Switching Mode Power Supplies", IEEE Transactions on electromagnetic compatibility, vol. 47, Issue 4, 2005, pp- 921-929.

[68] Shreenivas Jog, Nidhi Chaturvedi, Suvidha Chitnis, "Electromagnetic Compatibility of Energy Efficient Switched Mode Power Supply (SMPS) with CISPR EMI Standards", International Conference on Energy Systems and Applications (ICESA) 2015, pp- 700-705.

[69] Ankit Bhargava, David Pommerenke, Federico Centola, Cheung-Wei Lam, Keong Kam, Xin Chang, Robert Steinfeld, "EMI Prediction in Switched Power Supplies by

Full wave and Non-linear Circuit Co-simulation", International Symposium on Electromagnetic Compatibility, IEEE, 978-1-4244-4267-6/09, 2009, pp 41-46.

[70] K. K. Tse, Henry Shu-hung Chung, S. Y. R. Hui and H. C. So, "Spectral Characteristics of Randomly Switched PWM DC/DC Converters Operating in Discontinuous Conduction Mode" IEEE Transactions on industrial electronics, vol. 47, No. 4, 2000, pp-759-769.

[71] S. Ye, W. Eberle, Y.-F. Liu, "A novel EMI filter design method for switching power supply," IEEE Trans Power Electronics, vol. 19, no. 6, 2004, pp. 1668-1678.

[72] David A. Williams, "A Tutorial on EM1 Characterization of Switching Regulators Frequency of Emission (MHZ)", IEEE Applied Power Electronics Conference and Exposition, 1996, pp. 333-339.

[73] Qingbin Chen, Fengchun Ye, Wei Chen, "The Prediction of Conducted EMI on Switched Mode Power Supply Based on Full-circuit Simulation", IEEE 2nd International Future Energy Electronics Conference (IFEEC), Taipei, 2015, pp. 1-5.

****