ANALYSIS OF ENERGY STORAGE SYSTEMS BY USING PMSG IN REMOTE AREA POWER SUPPLY SYSTEMS

A Thesis Submitted
In Partial Fulfillment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING
(POWER SYSTEM & CONTROL)

by

ROHIT SINHA
(Enrollment No.:- 11804500807)
(University Roll No.:- 1180450003)

Under the Supervision of

Mr. V.K. Maurya
(Associate Professor & Head of Department,
Electrical Engineering)

to the
School of Engineering

BABU BANARASI DAS UNIVERSITY
LUCKNOW, UTTAR PRADESH

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CERTIFICATE

It is certified that the work contained in this thesis entitled **"ANALYSIS OF ENERGY STORAGE SYSTEMS BY USING PMSG IN REMOTE AREA POWER SUPPLY SYSTEMS"** by **Rohit Sinha (Roll No.:- 1180450003)**, for the award of **Master of Technology** from Babu Banarasi Das University, Lucknow, Uttar Pradesh has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

Signature

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Lucknow, Uttar Pradesh

Date :

Place :

CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in the thesis entitled **"ANALYSIS OF ENERGY STORAGE SYSTEMS BY USING PMSG IN REMOTE AREA POWER SUPPLY SYSTEMS"** is in partial fulfilment for the award of **"Master of Technology"** in Department of Electrical Engineering with specialization in **Power System and Control** is submitted to the **Department of Electrical Engineering, School of Engineering, Babu Banarasi Das University, Lucknow** is a record of my own investigations under the guidance of **Mr. V.K.Maurya, Associate Professor and Head of Department, Department of Electrical Engineering, Babu Banarasi Das University, Lucknow.** I have not submitted the matter presented in this thesis anywhere for the award of any other degree.

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ABSTRACT

In rural areas, the RAPS network has been used to supply power where the utility grid is not present or not easily available. The RER are now being used in RAPS network in order to reduce the high expenditure due to use of conventional generators. The RER have gained popularity nowadays against conventional generators. Therefore, it becomes very difficult to maintain the stability and reliability of RAPS systems. So, Permanent Magnet Synchronous Generator (PMSG) is gaining attention. This work suggests hybrid energy storage systems (HESS) such as ultra-capacitors (UCs) and Lithium-ion batteries to be interfaced into a PMSG based RAPS network to provide the frequency support and improve stability and reliability of the system. The UCs deal with fast changing frequency, whereas the Lithium-ion batteries provide primary frequency response. This work also suggests to carry out MPPT (Maximum power point tracking) strategy in order to deliver maximum power to the RAPS network. This work also suggests to use a PID or PI controller at the inverter or load end of the network in order to enhance the response characteristics. It will finally lead to enhancing the frequency regulation of the RAPS network. This work will help to achieve the goal of eco-friendly electrification. A hybrid energy storage system (HESS) comprising Lithium-ion batteries and UCs in a wind turbine using permanent magnet synchronous generator (PMSG) in remote area power supply (RAPS) network was developed, modelled and simulated using MATLAB and the observations were recorded and observed.

Keywords: PMSG-Permanent Magnet Synchronous Generator, RAPS- Remote Area Power Supply, UCs - Ultra-Capacitors, WECS - Wind Energy Conversion Systems, PCC - Point of Common Coupling, RER - Renewable Energy Resources & HESS - Hybrid Energy Storage Systems.

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Finally, yet importantly, I would like to express my heart full thanks to my parents to give invaluable support in all the circumstances that exhibited a high degree of patience and kept my moral always high.

ROHIT SINHA

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LIST OF ABBREVIATIONS

ABBREVIATIONS	DESCRIPTION
PMSG	Permanent Magnet Synchronous Generator
RAPS	Remote Area Power Supply
UCs	Ultra-Capacitors
WECS	Wind Energy Conversion Systems
PCC	Point of Common Coupling
RER	Renewable Energy Resources
HESS	Hybrid Energy Storage Systems
MPPT	Maximum Power Point Tracking
PID	Proportional-Integral-Derivative
PI	Proportional-Integral
THD	Total Harmonic Distortion
BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Semi-conductor Field Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
MATLAB	MATrix LABoratory

CHAPTER-1
INTRODUCTION

1.1 INTRODUCTION TO RESEARCH AREA

In order to reduce the dependent nature of fossil fuel, we have to rely on renewable energy (e.g., wind, solar) based remote area power supply (RAPS) systems. One main problem with renewable power generation is that it cannot be used as per demand and as per requirements, which is possible with conventional energy resources such as thermal and hydro. Therefore, it becomes very difficult for the conventional generators to meet the load side requirements in RAPS systems.

Remote area power supply (RAPS) system is an isolated power system that usually supplies power to small rural areas. These areas do not have access to the utility grid, and it is impossible to extend the utility grid to these areas. According to the international energy agency report, 1 billion people worldwide do not have access to electricity. RAPS systems are considered to be the best option for electrification and highly promoted by the Energy Access Practitioner Network launched by the United Nations Foundation to ensure universal access to modern energy service. Conventional generators such as diesel generator sets are widely being used in RAPS systems. However, due to the decrement of fossil fuel reserves, increasing prices and environmental issues, renewable energy resources are becoming more popular in RAPS systems. The RAPS system can be defined as a small electricity network which serves a single property owner with very simple loads or several communities with complex and inter-connected power stations. The typical feature of a RAPS system is that it remains isolated from the main utility grid. The generators in a RAPS system supply power to a cluster of loads, and the system balances generation and demand autonomously. The 'autonomous power systems' are also designed for electrification of regions without large transmission networks. Their capacity can be ranging from a few hundred Watts to tens or hundreds of mega-Watts. It can be seen that the definition of autonomous power systems is also same to that of the RAPS system. RAPS systems always operate in standalone mode and do not take any energy from the utility grid. Additionally, energy storage devices are commonly used in both micro-grid and RAPS system to remove the impact of fluctuation of non-dispatchable energy resources and improve system stability and reliability. Hence, storage devices may have relatively smaller capacity as compared to the RAPS system of comparable size. In micro-grids, advanced communication infrastructures are usually applied to realise centralised control schemes, which can be costly and impractical for RAPS systems considering the budget limitation and geographical constraints. As the micro-grids are connected to the utility grid, certain power quality requirements such as voltage, frequency and harmonic emission must be maintained according to the utility grid-code standards at the point of common coupling (PCC). However, RAPS systems are not obliged to maintain such rigorous grid-code standards. The voltage and frequency at the PCC is commonly used as the reference for the micro-grid, whereas RAPS system has to establish its own voltage and frequency references.

The low inertia characteristics of the RAPS system results in system's high sensitivity to the mismatch between generation and load demand. Large frequency excursions are common in such systems. The adoption of power electronics based renewable power generators such as wind energy conversion systems (WECSs) removes the frequency stability problem since these generators are not involved in frequency regulation. The WECS is being developed due to very high capacity and achieving popularity in remote areas like offshore where wind resource is abundant but the harsh environment demands a greater degree of reliability on WECS. Permanent magnet synchronous generator (PMSG) based WECS with full-scale converter is a good option to meet this requirement. PMSG is suitable for wind power generation due to its high torque-to-volume ratio, elimination of the excitation windings and its capability of direct drive variable speed operation without a gearbox. Therefore, PMSG is gaining attention on its contribution to frequency regulation.

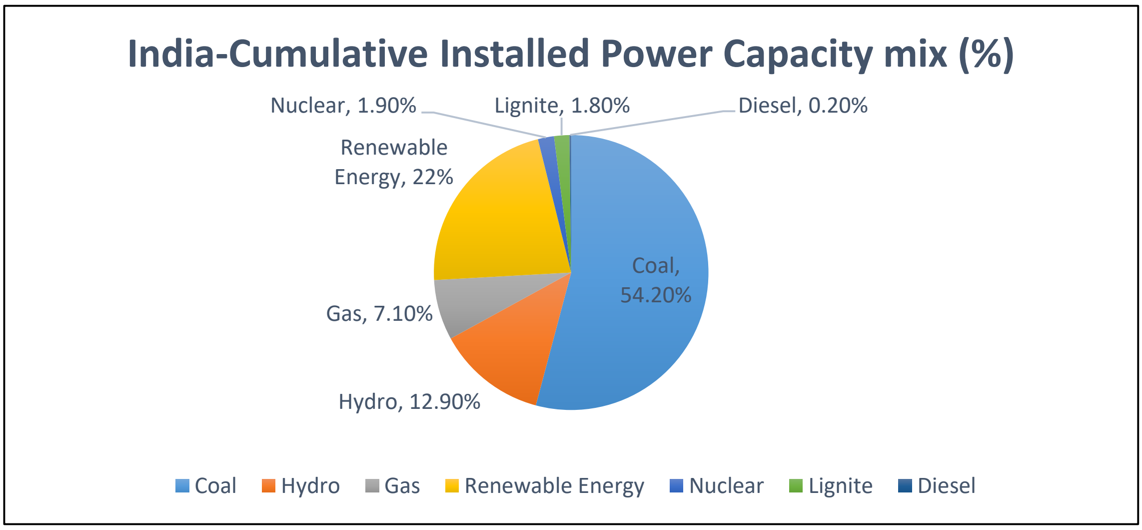

Figure 1.1: Pie-chart of installed power capacity as on 31 Dec 2018

Figure-1.1 shows the pie-chart representation of the installed power capacity in India as on 31 Dec 2018. From the pie-chart, it has been seen that "coal" occupies the major contribution to the installed power capacity which is around 54.2%. Coal is used as a major raw materials for the power plants for power generation purposes. The rest are hydro-12.9%, gas-7.1%, nuclear-1.9%, lignite-1.8%, diesel-0.2% and renewable energy-22%. Out of all these, the total losses or waste to power is about 0.04%. Out of the total 22% of renewable energy, wind power occupies around 10%, solar power occupies around 7.9%, bio-power occupies around 2.8% and small hydro occupies around 1.3%. The above data is of CEA, MNRE as on 31 Dec 2018.

Figure-1.2 shows the representation of electricity generation in India for the financial year 2018-19. Here, the thermal energy occupies the large area having larger contribution. The rest are nuclear, hydro, wind, solar, bio-mass, bagasse, small hydro and other renewables have also contributed to the electricity generation in India. The total electricity generation in India till the financial year 2018-19 is about 1376 BU (billion units). The above data is of CEA.

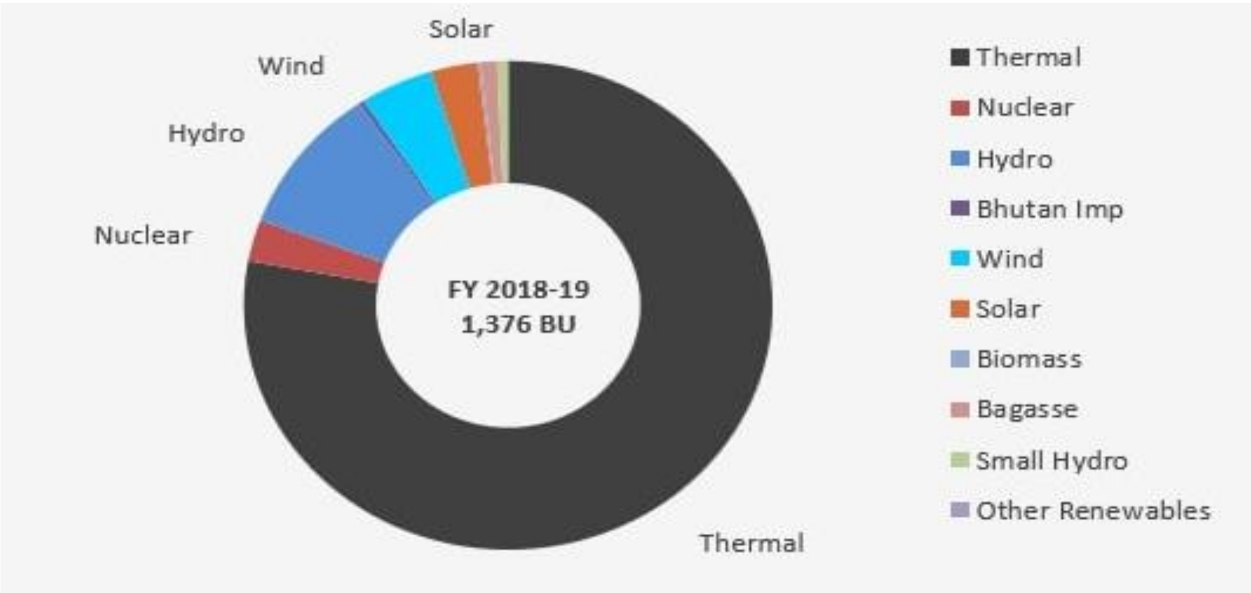

Figure 1.2: Representation of Electricity generation in India till the financial year 2018-19

Figure-1.3 shows the renewable energy capacity growth across different countries/ regions of the world. It shows the capacity growth achieved in GW (giga watts) during the years 2011-2016 and the target set to be achieved during the period 2017-2022. China has the highest growth capacity as compared to other countries/ regions across the world.

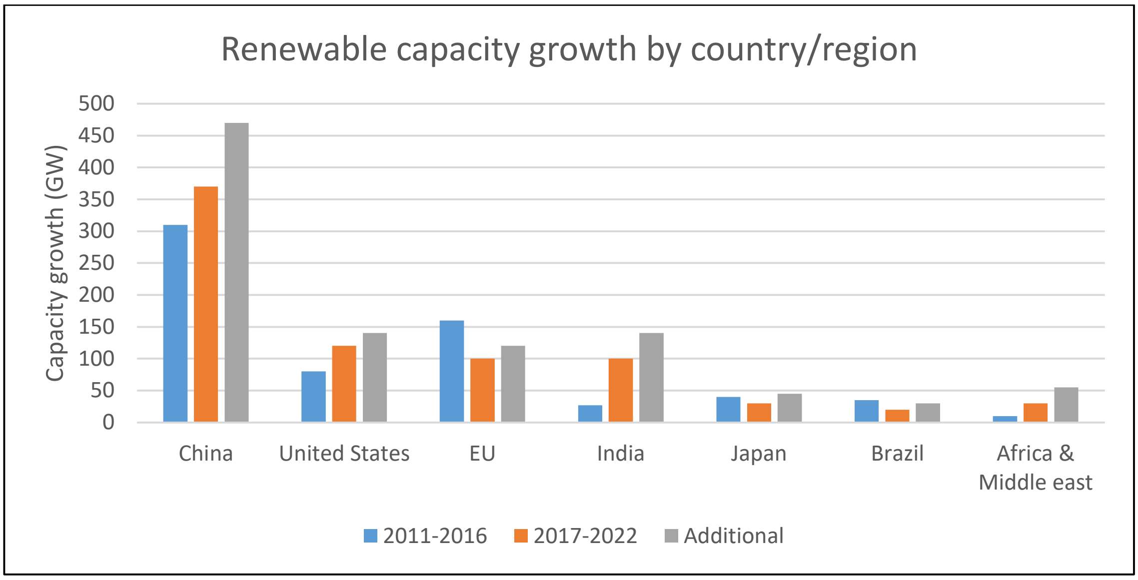

Figure 1.3: Representation of renewable capacity across different countries/ regions

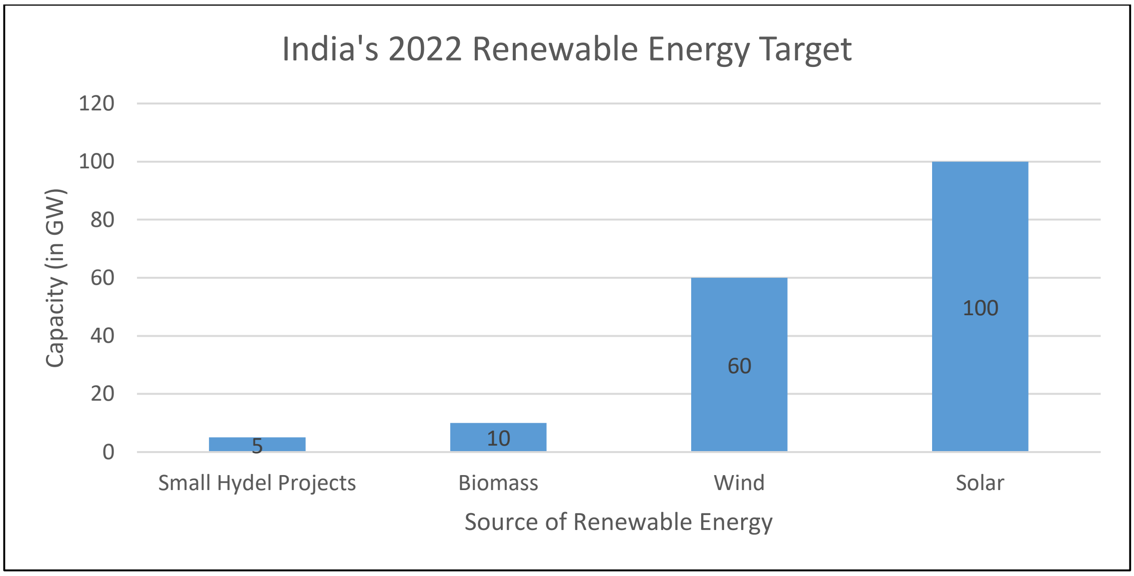

Figure 1.4: Chart representation of India's renewable energy target till 2022 with different sources of energy

Figure-1.4 shows the chart representation of India's renewable energy target till 2022 with different sources of energy. Out of all this, Solar energy has the highest target of 100 GW (giga watts). The Solar energy projects comprise of 40 GW of ultra-mega park solar projects, 40 GW of rooftop solar projects and 20 GW of utility scale solar projects. The rest are wind energy having 60 GW target, biomass energy having 10 GW and small hydel projects having 5 GW.

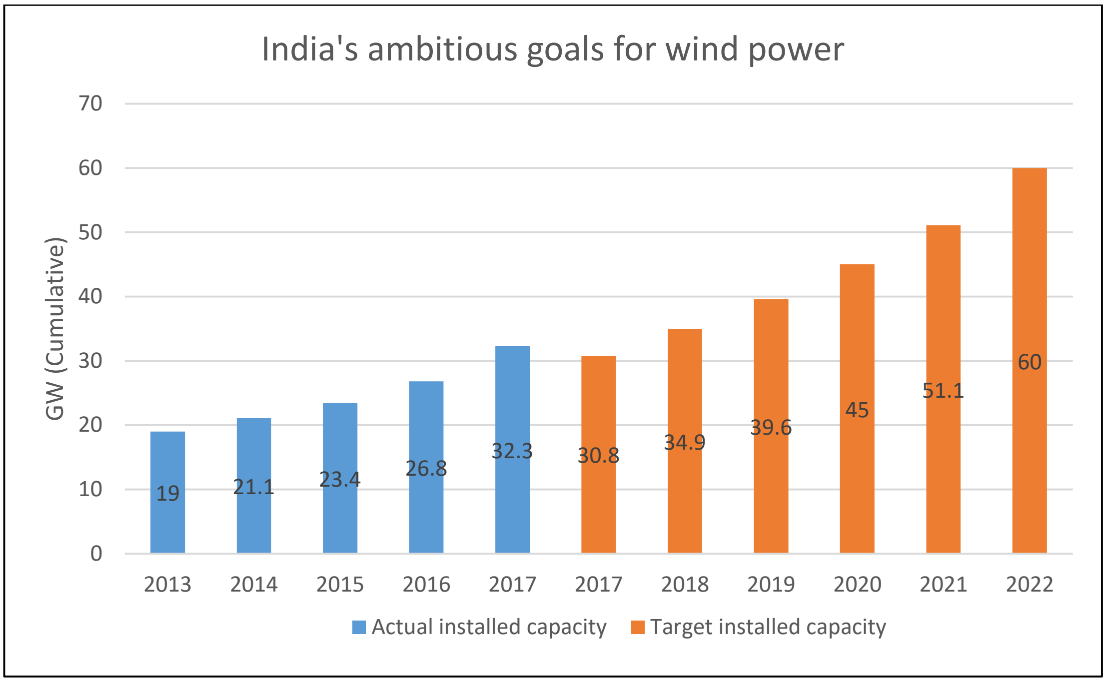

Figure 1.5: Chart representation of India's ambitious goal for wind power till 2022

Figure-1.5 shows the chart representation of India's ambitious goal for wind power till 2022. The goal set till 2022 for wind power is about 60 GW (giga watts). Till 2017, 32.3 GW (giga watts) have been installed across different regions of India. Till 2017, the set goal for wind power installation was about 30.8 GW. But more 1.5 GW have been installed across different regions of India. This is also considered as to be an achievement for India. The data is of Ministry of New and Renewable energy, India.

Figure-1.6 shows the chart representation of global new investment in clean energy in billion $ till 2018. The clean energy comprises energy from different sources like solar, wind, energy smart technologies, bio-mass and waste, bio fuels, small hydro, low carbon service, geo-thermal and marine. In 2004, the global investment in clean energy was about 50 billion $ and now in 2018, the global investment in clean energy is about 330 billion $. So, the total investment in clean energy globally has been increased to about 280 billion $. The clean energy has gained more popularity nowadays in terms of different sources of energy.

Figure-1.7 shows the block diagram representation of power generation in RAPS systems by using PMSG. Here, the wind turbine is rotated by the help of wind speed and is integrated into a PMSG so that the mechanical torque and power is generated. The power generated is fed into a rectifier and then to an inverter and then finally to the RAPS systems. In between, rectifier end and inverter end, hybrid control strategies are suggested like involvement of Ultra-capacitors and Lithium-ion batteries. The MPPT (Maximum power point tracking) strategy is also suggested to be carried out at the rectifier end of the network or system in order to deliver the maximum power to the system. A grid side controller at the inverter side is also suggested in order to enhance the response characteristics of the whole network or the system. The grid side controller may be a PID or PI controller in order to enhance the response characteristics of the whole network or the system.

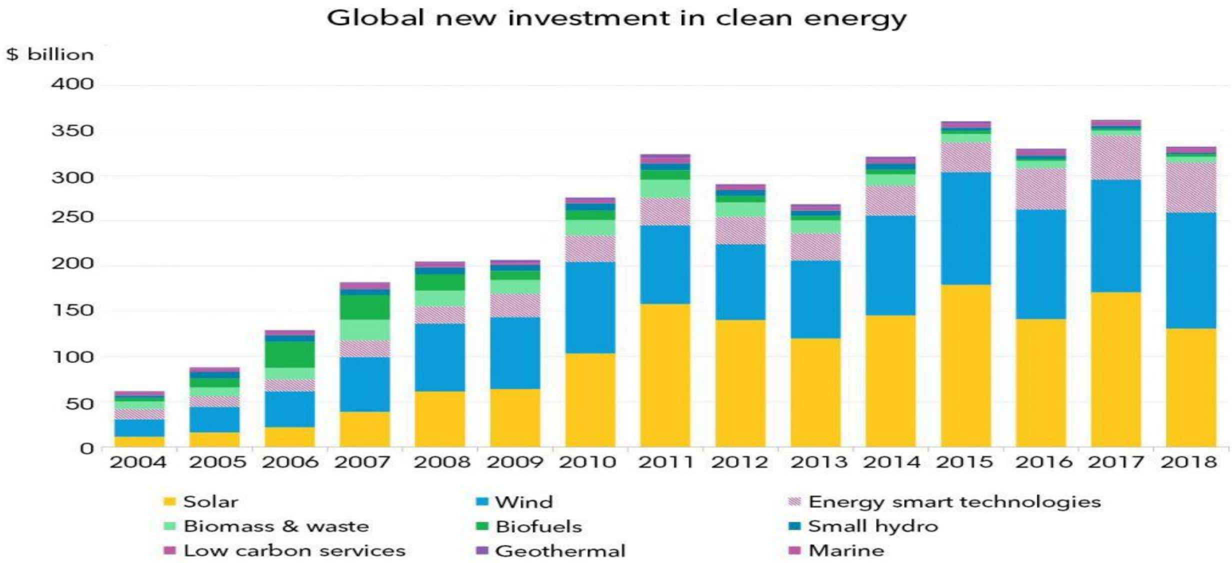

Figure 1.6: Chart representation of global new investment in clean energy in billion $ till 2018

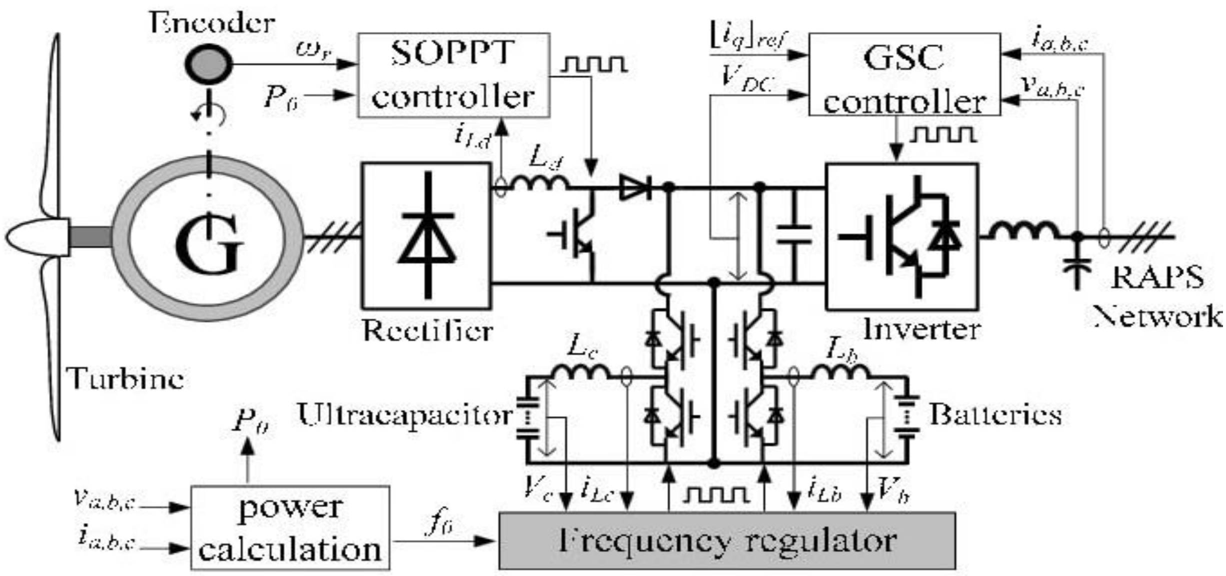

Figure 1.7: Block diagram representation of power generation in RAPS systems by using PMSG

1.2 MOTIVATIONAL STATEMENT

In rural areas, the RAPS network has been used to supply power where the utility grid is not present or not easily available. The RER are now being used in RAPS network in order to reduce the high expenditure due to use of conventional generators. To reduce the financial losses and power failure problems, RER are being widely used. The RER have gained popularity nowadays against conventional generators. Therefore, it becomes very difficult to maintain the stability and reliability of RAPS systems.

The renewable energy (e.g., wind, solar) are a need of the time in order to reduce the dependent nature of fossil fuels. The main problem with renewable power generation is that it cannot be used as per demand and as per requirements. They cannot be taken away from one place to another for different purposes. The conventional energy resources, such as thermal and hydel can be used as per demand and as per requirements. The use of RER has played a vital role on the operations of RAPS systems. Therefore, it becomes very difficult to maintain the stability and reliability of RAPS network. Nowadays, it has become very difficult for conventional generators to meet the requirements of the RAPS systems for their proper functioning.

RAPS system is an independent type of network that supplies power to small rural areas. In rural areas, the grid is not available and it is impossible to extend the grid to these areas. RAPS systems are considered to be the best option for electrification and highly promoted by the Energy Access Practitioner Network launched by the United Nations Foundation to ensure universal access to modern energy service. The diesel generator sets have been widely being used in RAPS network to maintain the supply. The RER based RAPS systems have gain more popularity nowadays due to the decrement of fossil fuel reserves and the increment of prices of the fuels. The RAPS system is a small network of electricity that serves as a unique owner of a system with very simple loads. The RAPS system tends to remain away from grid or remains isolated from the main utility grid. The RAPS systems are somewhat similar to the 'autonomous power systems'. RAPS systems always operate in isolated or independent mode and do not take any kind of support from the utility grid. The energy storage devices are commonly being used in the RAPS system to remove the fluctuation due to RER and to improve the stability and reliability of the system.

The adoption of renewable power generators such as wind energy conversion systems (WECSs) removes the problem of frequency stability. The WECS has been developed due to their high capacity and gaining popularity in rural areas and locations where wind resource is easily or likely available. Permanent magnet synchronous generator (PMSG) based WECS with energy storage devices will be a good option for this type of requirement. Therefore, PMSG is considered to be the best due to its high torque-to-volume ratio and its operational characteristics without a gearbox. Therefore, PMSG has gained attention nowadays.

1.3 PROBLEM STATEMENT

The research work has to be carried out with some objectives. The objectives of research has to meet certain criteria and need to overcome the problem statement which we have taken into consideration on undergoing extensive literature survey or literature review. A lot of research work has already been conducted on WECS (wind energy conversion systems), renewable generators like DFIG (doubly-fed induction generators) and conventional generators for supplying power in RAPS (remote area power supply systems). Remote area power supply (RAPS) system is an isolated power system that usually supplies power to small rural areas. These areas do not have access to the utility grid, and it is impossible to extend the utility grid to these regions. Some of the major problem statement which we will focus on while conducting our research work are mentioned as follows:-

i. Renewable power generation cannot be used as per demand and as per requirements, as in the case of conventional energy resources such as thermal and hydel.
ii. Large frequency disturbances are common in RAPS systems.
iii. RAPS systems are less reliable.
iv. RAPS systems are less stable.
v. Conventional generators such as diesel generators (DGs) are expensive to be utilized in RAPS systems.
vi. RAPS systems are usually small rural and remote communities. So, the facilities of utility grid cannot be extended to the rural or remote communities.
vii. It is technically and economically infeasible to extend the utility grid to rural or remote communities.
viii. Renewable power generators are unable to provide the frequency support to the RAPS systems. The frequency regulation capability is less.

ix. The off-line maintenance cost is more in these type of systems. It may lead to financial loss.
x. There are more chances of damage to system components in these type of systems.

1.4 OBJECTIVE OF RESEARCH

The research is to be carried out with certain objectives. The research will be carried out in order to meet the certain desired objectives. Some of the major certain desired objectives which we have taken into consideration in order to carry out our research work are mentioned as follows:-

i. To suggest innovative techniques in order to enhance the reliability of power supply in remote area power supply (RAPS) systems.
ii. To improve the stability of remote area power supply (RAPS) systems.
iii. To provide short term and long term frequency responses of RAPS systems.
iv. To provide eco-friendly electrification.
v. To provide economic and social benefits to the rural and remote communities.
vi. To extend the facilities of utility grid to the rural or remote communities or RAPS systems.
vii. To provide frequency regulation in RAPS systems.
viii. To analyze the energy storage systems by using PMSG in RAPS systems.

1.5 SCOPE OF RESEARCH

The research is to be carried out with some scope of it. As one may questioned us “Why we should carry out research?” or “What benefits we may get if we are carrying out this research work?” or “Whether the research work has some advantages or not?”. Keeping in view of all this, we have some scopes related to our research work. Some of the major scopes of our research work which we have taken into consideration are mentioned as follows:-

i. It has a wide variety of scope in order to maintain the power supply in the RAPS systems.
ii. It can be widely used by the industries in implementing it in order to supply power widely in the RAPS systems.
iii. To suggest innovative techniques in order to enhance the reliability of power supply in remote area power supply (RAPS) systems.

iv. To improve the stability of remote area power supply (RAPS) systems.
v. To provide frequency regulation in RAPS systems.
vi. To analyze the energy storage systems by using PMSG in RAPS systems.

1.6 OUTLINE OF THESIS

The layout of the thesis is given as below:-

Chapter-2- This chapter deals with the literature survey carried out in our research work related to RAPS system. The literature review deals with the literature taken into consideration while carrying out the research work. The main components which are taken for research work are also described here in detailed form.

Chapter-3- This chapter deals with the hybrid energy storage systems by using PMSG in the RAPS systems. The hybrid energy storage systems used here are Ultra-capacitors and batteries. A Simulink/ MATLAB model is prepared and the observations are recorded and observed here. This chapter aims at improving the stability and reliability of the RAPS systems.

Chapter-4- This chapter deals with the Maximum power point tracking (MPPT) strategy for a PMSG based RAPS network. The Simulink model consisting of boost converter with hybrid energy storage system (HESS) of a PMSG based RAPS system is simulated and the observations are recorded and observed here. This chapter aims at finding the maximum power and the maximum power point of the entire system.

Chapter-5- This chapter deals with the use of PID and PI Controllers with a PMSG based RAPS network. The Simulink model consisting of hybrid energy storage systems (HESS) of a PMSG based RAPS network along with PID and PI Controller is simulated and the observations are recorded and observed here. This chapter aims at improving the system frequency and improving the stability and reliability of the RAPS systems.

Chapter-6- This chapter deals with the results of the entire thesis.

Chapter-7- This chapter deals with the conclusion and future scope of work of the entire thesis.

Chapter-8- The references of the entire thesis work are mentioned in this chapter.

CHAPTER-2
LITERATURE SURVEY

2.1 LITERATURE REVIEW

In order to carry out our research work, we have done an extensive literature survey or literature review. There are a number of literatures based on regulating power supply in an RAPS network or system. Some of the most important literatures which are mostly related to our research work are do hereby mentioned here.

In 2007, a paper [31] discussed about the capability of doubly fed induction generator (DFIG) wind turbine for frequency regulation. It also discussed about the possibility of de-loading a wind turbine to provide primary and secondary frequency responses. This paper showed how a DFIG wind turbine can provide high frequency response. In 2008, a paper [30] discussed about the frequency response capability of the full converter variable speed wind turbine generator (FCWTG) with permanent magnet synchronous generator (PMSG). It discussed about the control schemes for the frequency support for a wind farm. In 2009, a hand book [28] i.e. “Load frequency control and performance” discussed about the load frequency control methods. It also discussed about the control schemes- primary control, secondary control, tertiary control and time control with the system frequency. In 2009, a paper [27] discussed about the two level energy storage systems for application to wind energy systems. It discussed about the wind storage systems. In 2010, a paper [26] discussed about the hybrid energy storage system coupled in a wind turbine generator to smooth the wind power. It was studied by means of real time HIL simulation. In 2011, a paper [25] discussed about the stand alone ac power systems facing frequency fluctuations issues and power deviations issues. It implements the droop control system to reduce the noise and the parameter variations. In 2012, a paper [23] presented its view on wind turbine contribution to frequency control of non-interconnected island systems. It described transient frequency support (inertial response) and permanent frequency response (droop characteristics) as well as combination of both. In 2012, a paper [22] presented about dynamic simulations in order to study dynamic frequency control support by using energy storage systems. In 2013, a paper [21] came in “Elsevier” which discussed about different types of batteries and their behaviors to be utilized in off-grid renewable applications. The comparison was made and the result said that lithium-ion batteries have better characteristics than other batteries. In 2013, a paper [20] discussed about primary frequency contribution and smoothening power fluctuations due to changes in wind speed. The wind speed was changed in order to carry out its contribution. In 2014, a paper [17] discussed about the reactive power circulation effects on the back-to-back power converters in a DFIG based wind turbine system. In 2014, a paper [15] came in "Elsevier" which discussed about the RAPS system and its topology. It also discussed about the technical challenges in planning and operations of RAPS systems. In 2014, a paper [12] came in "Elsevier" which discussed about the electric energy storage techniques and their applications to power system operation and control. It also discussed about the different configurations in electric energy storage systems. This paper provided a state-of-the-art technologies and their technical challenges on electric energy storage.

In 2012, a paper [24] discussed about MPPT strategy for a solar photo-voltaic (PV) system. The MPPT strategy was done by using boost converter and perturb and observe (P&O) method. In 2014, a paper [19] discussed about the MPPT strategy for a PV system with intended ripple currents. The MPPT strategy is carried out by using boost converter. In 2014, a paper [16] discussed about the MPPT strategy for wind energy conversion system (WECS) using PMSG. The MPPT was carried out by using dc-dc boost converter. In 2015, a paper [13] discussed about MPPT for a PV system using probability and statistics. In 2016, a paper [9] discussed about MPPT for a variable speed PMSG based WECS. In 2018, a paper [5] discussed about the MPPT control strategy for a doubly fed induction motor based variable wind turbine. In 2019, a paper [2] discussed about MPPT strategy for a variable speed WECS. The MPPT strategy was carried out by using boost converter.

In 2015, a paper [14] discussed about the synthesis of PI, PD and PID controllers employing current conveyor trans-conductance amplifier (CCTA). The maximum power consumed by the circuit has been observed here. In 2016, a paper [11] discussed about the Ziegler Nichols tuning technique and Pade's approximation by using PI, PD and PID controllers. The responses are observed here.

In 2016, a paper [10] discussed about the frequency based approach using two different types of energy storage systems on an isolated system. The detailed analysis has been carried out on the isolated system using fourier transform. It also discussed about the low, intermediate and the cut-off frequency values during the analysis on isolated system. In 2016, a paper [8] suggested about multi-level energy storage systems in RAPS systems. It suggested to integrate HESS (lead-acid batteries and UCs) into a PMSG based RAPS network to provide the frequency support. The SOPPT (sub optimal power point tracking) strategy is proposed here to provide secondary frequency response. In 2016, a paper [7] discussed about the DFIG based wind generators to provide frequency support to the RAPS systems. In 2017, a paper [6] discussed about the PMSG based RAPS network including UCs. It also discussed about the enhanced frequency response strategy. In 2018, a paper [4] discussed about the combined wind and HESS to smooth wind power fluctuations and a fuzzy based wind-HESS system controller is proposed in this chapter. In 2018, a paper [3] discussed about the HESS systems consisting of battery and UCs to provide power management of virtual synchronous generators (VSGs). In 2019, a paper [1] discussed about integrating HESS including UCs and LABs into a PMSG based RAPS network to provide the frequency support. The enhanced frequency regulation of the network is also discussed here.

2.2 COMPONENTS INVOLVED IN OUR WORK

The main components involved in our work are as follows:-

i. Wind turbine.
ii. Permanent Magnet Synchronous Generator (PMSG).
iii. RAPS system.
iv. Ultra-Capacitors (UCs).
v. Batteries.
vi. Boost Converters.
vii. PID Controller.
viii. PI Controller.

i. Wind turbine:-

A wind turbine also known as wind energy converter, is used to convert the wind’s kinetic energy to electrical energy. A wind turbine consists of a turbine which is rotated by means of wind. The wind acts as an input to the wind turbine. The wind turbine is used to generate the mechanical torque, which is then taken as an input to get the electrical energy. The wind turbine has 2 different types of axis-vertical axis and horizontal axis. The smallest of all the wind turbines are used for providing power to traffic warning signs and charging of battery of boats. The larger turbines are used for domestic power supply purposes and have become an important source of renewable energy. Nowadays, many countries have started using wind turbines instead of using fossil fuels. The turbines can rotate in horizontal axis manner or vertical axis manner. The horizontal axis is the older one and the most common one. The wind turbines mostly have a gearbox. The wind turbines are mostly used for production of electric power commercially.

The wind turbine block in MATLAB is a function of wind speeds and pitch angle (beta). It mainly depends on the nature and speed of the wind. It is mostly used in wind farms or in areas where wind is mostly available.

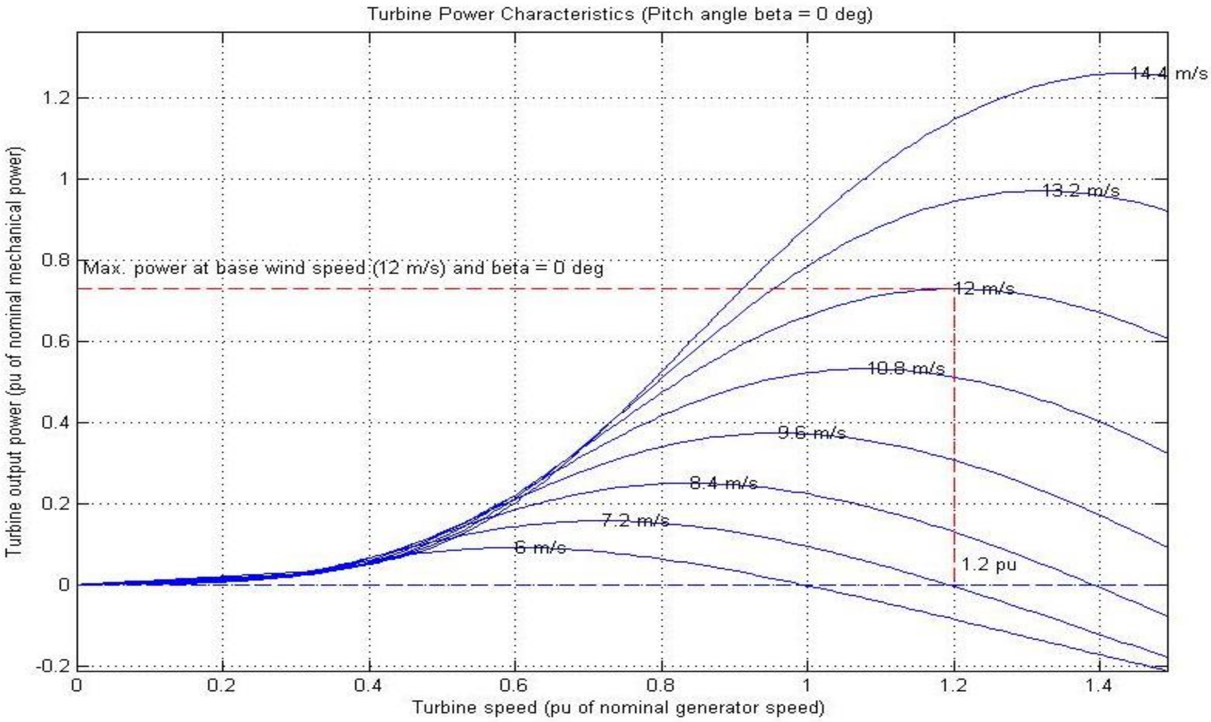

Figure 2.1: Wind turbine power characteristics at pitch angle beta=0 degrees

Figure-2.1 shows the wind turbine power characteristics of the wind turbine in MATLAB at pitch angle beta = 0 deg. From this figure, the wind turbine delivers maximum power or maximum turbine power output at 12 m/sec wind speed and at 1.2 p.u. turbine speed. The wind turbine delivers maximum power at 12 m/sec wind speed.

ii. Permanent Magnet Synchronous Generator (PMSG):-

PMSG stands for permanent magnet synchronous generator. It is a type of generator where the permanent magnet provides the excitation field. The term synchronous refers to the fact that the rotor and stator rotate with the same speed, and permanent magnet generates the magnetic field and current gets induced into the armature. In commercial purposes, the major source of electrical energy is provided by synchronous generators.

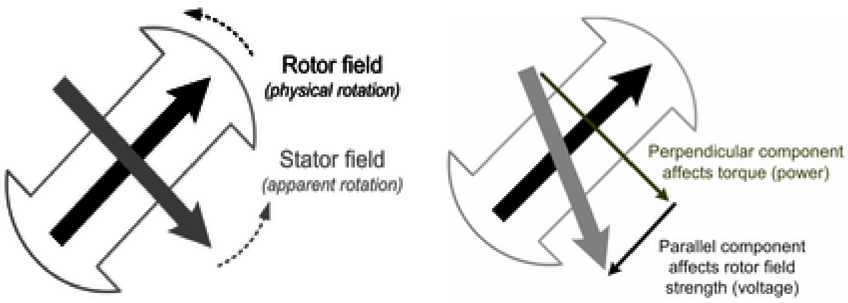

Figure 2.2: Rotor and stator fields in PMSG

In PMSG, the "rotor" is the permanent magnet, and the "stator" is the armature, which is connected to the load end. The rotor and stator parts of the PMSG are shown in figure-2.2. Both the stator and the rotor maintain their synchronism with respect to their rotation. The rotor i.e. permanent magnet of the PMSG rotates due to the input given as mechanical torque by the wind turbine. The movement of permanent magnet leads to generate flux which in turn leads to generate the emf and finally leads to generate the voltage at the armature windings. The output voltages of PMSG consists of three phase voltages, which are phase shifted to each other by an angle of 120 degrees. The stator winding of the PMSG carries the three phase armature windings and is electrically displaced by 120 degrees from each other producing an AC voltage output, as shown in figure-2.3.

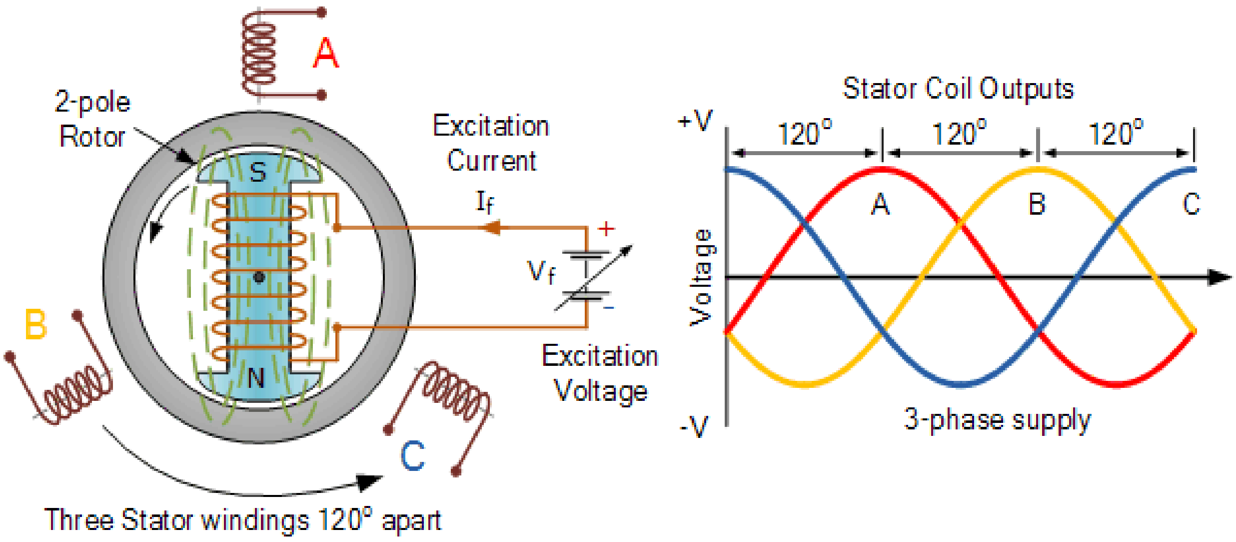

Figure 2.3: Construction of PMSG

In MATLAB, the PMSG is made from Permanent Magnet Synchronous Machine block. Here, the input of Permanent Magnet Synchronous Machine is taken as mechanical torque which makes it as PMSG. The PMSG acts as a generator.

iii. RAPS system:-

RAPS system is an independent type of network that supplies power to small rural areas. In rural areas, the grid is not available and it is impossible to extend the grid to these areas. RAPS systems are considered to be the best option for electrification and highly promoted by the Energy Access Practitioner Network launched by the United Nations Foundation to ensure universal access to modern energy service. The diesel generator sets have been widely being used in RAPS network to maintain the supply. The RER based RAPS systems have gain more popularity nowadays due to the decrement of fossil fuel reserves and the increment of prices of the fuels. The RAPS system is a small network of electricity that serves as a unique owner of a system with very simple loads. The RAPS system tends to remain away from grid or remains isolated from the main utility grid. The generators used in a RAPS system supplies the required voltage to the network and the system maintains their load demand accordingly. The RAPS systems are somewhat similar to the ‘autonomous power systems’. RAPS systems always operate in isolated or independent mode and do not take any kind of support from the utility grid. The energy storage devices are commonly being used in the RAPS system to remove the fluctuation due to RER and to improve the stability and reliability of the system.

The renewable energy (e.g., wind, solar) is a need of the time in order to reduce the dependent nature of fossil fuels. The main problem with renewable power generation is that it cannot be used as per demand and as per requirements. They cannot be taken away from one place to another for different purposes. The conventional energy resources, such as thermal and hydel can be used as per demand and as per requirements. The use of RER has played a vital role on the operations of RAPS systems. Therefore, it becomes very difficult to maintain the stability and reliability of RAPS network. Nowadays, it has become very difficult for conventional generators to meet the requirements of the RAPS systems for their proper functioning.

iv. Ultra-Capacitors (UCs):-

An ultra-capacitor is known as super-capacitor. It is an electrical component capable of holding electrical charge hundreds of times than a standard capacitor. It is useful in devices which require low current and low voltage. They are normally used in emergency radios and flashlights.

Figure 2.4: A typical Ultra-capacitor

The UC requires charging before its mode of operation. Once the UC is fully charged, it can function for some period of time till it gets fully discharged or it requires charging. Once it is fully charged, then current stops flowing and the UCs output voltage is equal to the voltage of the supply. A fully charged UC will store energy till it gets fully discharged. When the UC is in discharging mode, then the stored energy gets converted into electrical energy to supply to the load present within the network. UCs are always connected in parallel manner with the network. UCs comprises of a very high value of capacitor and very less value of resistor connected in series manner. A high value of capacitor and less value of resistor are connected in series manner and the whole arrangement is connected in parallel with the circuit or the network. It always contains very high value of capacitance.

v. Batteries:-

A battery consists of one or more electro-chemical cells, which are connected to provide power to the devices like flashlights, smartphones, etc., In MATLAB, the battery (mask) is present, in which different types of batteries are found, which are connected in series with the circuit. There are many different types of batteries in MATLAB. Any one type of battery can be chosen at a time. Here, we have used lithium-ion battery.

vi. Boost Converters:-

Boost Converters are usually DC-DC converters. They are also known as step-up converters. It is used to step-up the voltage to a voltage which is greater than the source voltage. It is used for DC to DC conversion purposes. Here, the output voltage is always higher than the input voltage.

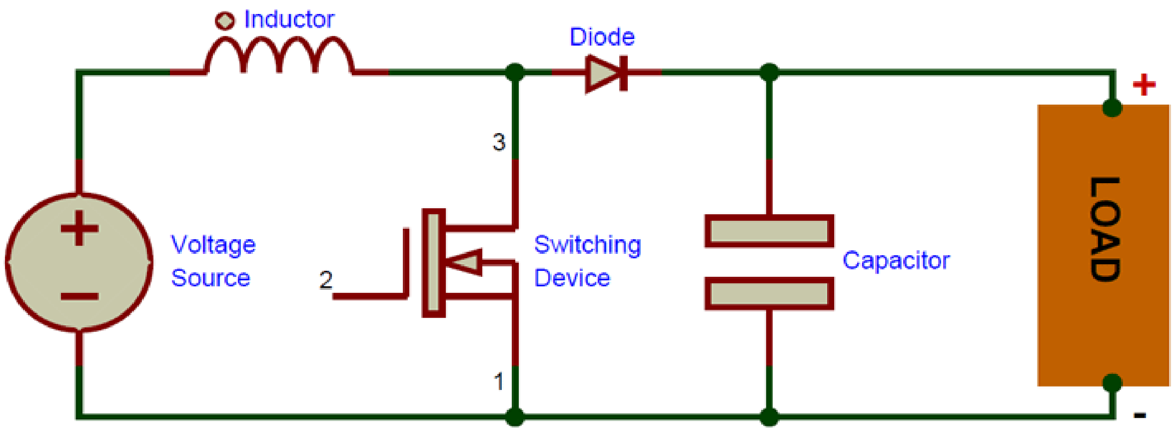

Figure 2.5: Circuit diagram of Boost Converter

It consists of an inductor, a semi-conductor switch or switching device, a diode and a capacitor connected across the load. Figure-2.5 shows the circuit diagram of boost converter. The switching device may be a IGBT, MOSFET or BJT. The boost converters have high efficiency. Here, when the switch or switching device is closed, the current flows through the inductor branch and the inductor stores some energy by generating a magnetic field. When the switch is open, current gets reduced and the magnetic field previously created gets destroyed to maintain current towards the load. At this point, a higher voltage comes into account to charge the capacitor through the diode. Hence, a higher voltage comes into action which is greater than the source voltage.

vii. PID Controller:-

A PID Controller is a proportional-integral-derivative controller. It has the ability to use proportional, integral and derivative on the controller output signal to apply and give an accurate and optimal controlled output signal. It is widely used in industrial control systems. The PID controller continuously calculates the error value, i.e., the difference between the set point value and the measured value and then applies the proportional, integral and derivative terms to give the accurate and optimally controlled output signal. Its main objective is to minimize the error value. The calculations regarding PID controller are usually done by the help of Laplace transformation which is usually in s-domain. The proportional, integral and derivative terms are summed up to get the output of the PID Controller. The advantages of the PID controller are fast reaction to disturbances, faster computations and accurate set point temperature control.

viii. PI Controller:-

A PI Controller is a proportional-integral controller. It has the ability to use proportional and integral on the controller output signal to apply and give an accurate and optimal controlled output signal. Here, the derivative part of the controller is not used or the derivative part is set to zero. The calculations regarding PI controller are usually done by the help of Laplace transformation which is usually in s-domain. The proportional and integral terms are summed up to get the output of the PI Controller. The disadvantage of PI controller is slow reaction to disturbances.

CHAPTER-3

HYBRID ENERGY STORAGE SYSTEMS BY USING PMSG IN REMOTE AREA POWER SUPPLY (RAPS) USING MATLAB

3.1 INTRODUCTION

The renewable energy (e.g., wind, solar) is a need of the time in order to reduce the dependent nature of fossil fuels. The main problem with renewable power generation is that it cannot be used as per demand and as per requirements. They cannot be taken away from one place to another for different purposes. The conventional energy resources, such as thermal and hydel can be used as per demand and as per requirements. The use of RER has played a vital role on the operations of RAPS systems. Therefore, it becomes very difficult to maintain the stability and reliability of RAPS network. Nowadays, it has become very difficult for conventional generators to meet the requirements of the RAPS systems for their proper functioning.

RAPS system is an independent type of network that supplies power to small rural areas. In rural areas, the grid is not available and it is impossible to extend the grid to these areas. RAPS systems are considered to be the best option for electrification and highly promoted by the Energy Access Practitioner Network launched by the United Nations Foundation to ensure universal access to modern energy service. The diesel generator sets have been widely being used in RAPS network to maintain the supply. The RER based RAPS systems have gain more popularity nowadays due to the decrement of fossil fuel reserves and the increment of prices of the fuels. The RAPS system is a small network of electricity that serves as a unique owner of a system with very simple loads. The RAPS system tends to remain away from grid or remains isolated from the main utility grid. The generators used in a RAPS system supplies the required voltage to the network and the system maintains their load demand accordingly. The RAPS systems are somewhat similar to the 'autonomous power systems'. RAPS systems always operate in isolated or independent mode and do not take any kind of support from the utility grid. The energy storage devices are commonly being used in the RAPS system to remove the fluctuation due to RER and to improve the stability and reliability of the system.

The adoption of renewable power generators such as wind energy conversion systems (WECSs) removes the problem of frequency stability. The WECS has been developed due to their high capacity and gaining popularity in rural areas and locations where wind resource is easily or likely available. Permanent magnet synchronous generator (PMSG) based WECS with energy storage devices will be a good option for this type of requirement. Therefore, PMSG is considered to be the best due to its high torque-to-volume ratio and its operational characteristics without a gearbox. Therefore, PMSG has gained attention nowadays.

Energy storage devices like UCs and lithium-ion batteries will be a reliable option in order to improve the WECS based RAPS systems. The ultra-capacitor (UC) is a short range energy storage device due to its high efficiency and fast charging and discharging rates. These advantages of UC have led to support instantaneous load spikes. The UC is kept in order to maintain the dynamic frequency support whenever a disturbance in frequency takes place in the system. Here, in these types of areas, the capability of UC is limited with the primary frequency response that lasts less than 30 seconds. Batteries have high energy density and are considered suitable for long term frequency regulation. The drawback of batteries is that they degrade faster and reduces their cost. One of the approaches is to combine Lithium-ion batteries with UCs, that removes the drawbacks associated with the single energy storage system. Therefore, the hybrid energy storage system (HESS) may improve the frequency regulation of the independent isolated RAPS system. A Hybrid Energy Storage System (HESS) is inserted with the converters at the Point of Common Coupling (PCC) in order to improve the generation from wind turbines. Based on the Hybrid Energy Storage System (HESS), consisting of UCs and Lithium-ion batteries, the system is added on to the DC link of the entire network. The UCs provide the fast changing frequency, whereas the Lithium-ion batteries provide primary frequency response.

3.2 WORKING PRINCIPLE

The research work has to be carried out with the help of some tools like MATLAB software. So, the tool which we will be using in order to carry out our research work will be MATLAB R2013a 64 bit software. The elements like wind turbine block, PMSG (Permanent Magnet Synchronous Generator), rectifier block, inverter block, inductor, capacitor, 3-phase VI measurement block, LC filter block, ultra-capacitor block, battery block, 3-phase transformer, 3-phase RLC load block, etc. required in our work will be taken from “Sim power systems” tool box under “Sim scape” icon present in Simulink library of the MATLAB. We will be utilizing “Battery” and “Ultra-capacitors” block for hybrid energy storage systems for maintaining the power supply in the network or RAPS systems and improving the stability and reliability of the network. “Powergui” block is used as a generator to the model in order to make it run in MATLAB. We will also be utilizing “Scope” and “Workspace”-block under “Sink” icon present in Simulink library of the MATLAB in order to record the observations or responses after simulating the model. The model is made to run at 50 Hz frequency. First of all, all the blocks are initialized as per requirements and then the model is made to run to check if there are errors present in it or not. Then the Simulink model is made to run or simulate by using MATLAB R2013a 64 bit software tool. The responses are observed by the help of scope or workspace.

The HESS (UCs and Lithium-ion battery), is interfaced into a PMSG based WECS. First of all, the wind turbine rotates to generate the mechanical torque. Then, the torque is given as input to the PMSG. PMSG is used to convert the mechanical work done by the wind turbine to electrical energy. The output voltage of PMSG is given as input to the diode bridge rectifier. The diode bridge rectifier converts the input sinusoidal alternating voltage to the DC voltage and passes on to the associated network. The DC voltage is converted to alternating voltage by means of an IGBT/ diode based inverter. The energy storage devices, i.e., UCs and lithium-ion batteries are connected to the DC side, which is in between the rectifier and inverter end. It acts as a branch in between the rectifier and inverter end. The output power generation through IGBT/ diode bridge inverter is then made to pass through a three phase transformer by connecting a LC-filter in between them. The output is then provided further to the RAPS network system.

3.3 COMPONENTS

The components present in this work are as follows:-

i. Wind turbine.
ii. Permanent Magnet Synchronous Generator (PMSG).
iii. Diode bridge rectifier.
iv. IGBT/ Diode bridge inverter.
v. Ultra-Capacitors (UCs).

vi. Batteries.
vii. LC filter.
viii. Three phase transformer (Star-Delta).
ix. SVPWM generator (2-level).
x. Three phase V-I measurement.

i. Wind Turbine:

A wind turbine consists of a turbine which is rotated by means of wind. The wind acts as an input to the wind turbine. The wind turbine is used to generate the mechanical torque, which is then taken as an input to get the electrical energy. The wind turbine has 2 different types of axis-vertical axis and horizontal axis. The smallest of all the wind turbines are used for providing power to traffic warning signs and charging of battery of boats. The larger turbines are used for domestic power supply purposes and have become an important source of renewable energy. Nowadays, many countries have started using wind turbines instead of using fossil fuels. The turbines can rotate in horizontal axis manner or vertical axis manner. The horizontal axis is the older one and the most common one. The wind turbines mostly have a gearbox. The wind turbines are mostly used for production of electric power commercially.

The wind turbine block in MATLAB is a function of wind speeds and pitch angle (beta). It mainly depends on the nature and speed of the wind. It is mostly used in wind farms or in areas where wind is mostly available.

ii. Permanent Magnet Synchronous Generator (PMSG):

PMSG stands for permanent magnet synchronous generator. It is a type of generator where the permanent magnet provides the excitation field. The term synchronous refers to the fact that the rotor and stator rotate with the same speed, and permanent magnet generates the magnetic field and current gets induced into the armature. In commercial purposes, the major source of electrical energy is provided by synchronous generators.

In PMSG, the "rotor" is the permanent magnet, and the "stator" is the armature, which is connected to the load end. Both the stator and the rotor maintain their synchronism with respect to their rotation. The rotor i.e. permanent magnet of the PMSG rotates due to the input given as mechanical torque by the wind turbine. The movement of permanent magnet leads to generate flux which in turn leads to generate the emf and finally leads to generate the voltage at the armature windings. The output voltages of PMSG consists of three phase voltages, which are phase shifted to each other by an angle of 120 degrees. The stator winding of the PMSG carries the three phase armature windings and is electrically displaced by 120 degrees from each other producing an AC voltage output.

In MATLAB, the PMSG is made from Permanent Magnet Synchronous Machine block. Here, the input of Permanent Magnet Synchronous Machine is taken as mechanical torque which makes it as PMSG. The PMSG acts as a generator.

iii. Diode bridge rectifier:

The diode rectifier is used to convert the input AC voltage to DC voltage as the output. This process is known as rectification. A diode bridge rectifier consists of four or more diodes in a bridge circuit manner that provides the same polarity of output as that of input. It provides full-wave rectification.

The diode bridge rectifiers are implemented by using Universal bridge block in MATLAB. The Universal Bridge block consists of converters having six power switches connected in a bridge manner. The selection of switches and converters are done from the dialog box.

iv. IGBT/ Diode bridge inverter:

An inverter is used to convert the input DC voltage to AC voltage as the output. This process is known as inversion. This process can be achieved by thyristors, BJT, MOSFET, IGBT, etc. The output voltage of the inverter remains non-sinusoidal and rich in harmonics.

The IGBT/ diode bridge inverters are implemented by using Universal bridge block in MATLAB. The Universal Bridge block consists of converters having six power switches connected in a bridge manner. The selection of switches and converters are done from the dialog box.

v. Ultra-Capacitors (UCs):

An ultra-capacitor is known as super-capacitor. It is an electrical component capable of holding electrical charge hundreds of times than a standard capacitor. It is useful in devices which require low current and low voltage. They are normally used in emergency radios and flashlights.

The UC requires charging before its mode of operation. Once the UC is fully charged, it can function for some period of time till it gets fully discharged or it requires charging.

Once it is fully charged, then current stops flowing and the UCs output voltage is equal to the voltage of the supply. A fully charged UC will store energy till it gets fully discharged. When the UC is in discharging mode, then the stored energy gets converted into electrical energy to supply to the load present within the network. UCs are always connected in parallel manner with the network. UCs comprises of a very high value of capacitor and very less value of resistor connected in series manner. A high value of capacitor and less value of resistor are connected in series manner and the whole arrangement is connected in parallel with the circuit or the network. It always contains very high value of capacitance.

vi. Batteries:

A battery consists of one or more electro-chemical cells, which are connected to provide power to the devices like flashlights, smartphones, etc., In MATLAB, the battery (mask) is present, in which different types of batteries are found, which are connected in series with the circuit. There are many different types of batteries in MATLAB. Any one type of battery can be chosen at a time. Here, we have used lithium-ion battery.

vii. LC filter:

An LC filter consists of inductors (L) and capacitors (C) to form low-pass filter, high-pass filter, or band-pass filter. It is a passive type of filter. A LC filter block is used to reduce noise and to remove the ripples present within the signal. It consists of one inductor and one capacitor. Here, we have chosen a branch type LC filter. They are mainly used to remove ripples from the circuit.

viii. Three phase transformer (Star-Delta):

A three phase transformer or 3-phase transformer consists of three single-phase transformers. It consists of primary and secondary windings. The primary and secondary windings of a transformer can be connected in different configurations such as star or delta or as per requirement. Here, in MATLAB, we have used a three phase transformer star-delta d11 configuration and it is connected in series with the network and is used to convert the voltage from 11KV to 0.4KV, suitable to be supplied to the RAPS network.

ix. SVPWM generator (2-level):

SVPWM generator is used to generate pulses for PWM type of converters. It acts as a gating pulse provider for IGBT/ diode based inverter. It generates pulses for PWM converters using the space vector pulse width modulation (SVPWM) technique. It generates the six pulses required by a three-phase two-level voltage-sourced converter (VSC) consisting of three half-bridge switching devices like FETs, GTOs or IGBTs, etc.

x. Three phase V-I measurement:

Three phase V-I measurement block is used to measure the output voltages and currents in MATLAB. It is used to measure the output voltages and currents in per unit values or in volts or amperes. It is mainly used to measure the three phase voltages and currents. The measurement of the voltages can be done as phase-to-ground or phase-to-phase. Here, we have kept the measurements as phase-to-phase.

3.4 PARAMETERS TAKEN

i. Parameters of Wind Turbine:

Table 3.1: Parameters of wind turbine

Sl. No.	Parameter	Value
1.	Nominal mechanical output power (W)	1.5e6
2.	Base power of the electrical generator (VA)	1.5e6/0.9
3.	Base wind speed (m/s)	12
4.	Maximum power at base wind speed (pu of nominal mechanical power)	0.73
5.	Base rotational speed (p.u. of base generator speed)	1.2
6.	Pitch angle beta to display wind-turbine power characteristics (beta >=0) (deg)	0

ii. Parameters of PMSG:

Table 3.2: Parameters of PMSG

Sl. No.	Parameters	Values
1.	Number of phases	3

2.	Back EMF waveform	Sinusoidal
3.	Rotor type	Round
4.	Mechanical input	Torque Tm
5.	Preset model	No
6.	Stator phase resistance Rs (ohm)	0.425
7.	Armature inductance (H)	8.35e-3
8.	Flux linkage established by magnets (V.s)	1.225
9.	Inertia, viscous damping, pole pairs, static friction [J(kg.m^2) F(N.m.s) p() Tf(N.m)]	[2.26e-5 1.35e-5 10 0]
10.	Initial conditions [wm(rad/s) thetam(deg) ia,ib(A)]	[0,0, 12,12]
11.	Sample time	-1
12.	Rotor flux position when theta = 0	90 degrees behind phase A axis (modified park)

iii. Parameters of Diode bridge Rectifier:

Table 3.3: Parameters of Diode bridge Rectifier

Sl. No.	**Parameter**	**Value**
1.	Number of bridge arms	3
2.	Snubber resistance Rs (Ohms)	5e-3
3.	Snubber capacitance Cs (F)	1e-6
4.	Power Electronic device	Diodes
5.	Ron (Ohms)	3

6.	Lon (H)	0
7.	Forward voltage Vf (V)	11e3

iv. Parameters of IGBT/ Diode bridge inverter:

Table 3.4: Parameters of IGBT/ Diode bridge inverter

Sl. No.	**Parameter**	**Value**
1.	Number of bridge arms	3
2.	Snubber resistance Rs (Ohms)	5
3.	Snubber capacitance Cs (F)	1e-6
4.	Power Electronic device	IGBT/ Diodes
5.	Ron (Ohms)	3
6.	Forward voltages [Device Vf(V) , Diode Vfd(V)]	[11e3 0.7]
7.	[Tf (s) , Tt (s)]	[1e-6 2e-6]

v. Parameters of Ultra-Capacitors (UCs):

Table 3.5: Parameters of Ultra-Capacitors (UCs)

Sl. No.	**Parameter**	**Value**
1.	Resistance R (Ohms)	2e-3
2.	Capacitance C (F)	150

vi. Parameters of Batteries:

Table 3.6: Parameters of Batteries

Sl. No.	Parameter	Value
1.	Battery type	Lithium-Ion
2.	Nominal Voltage (V)	1.2
3.	Rated Capacity (Ah)	1.5
4.	Initial State-Of-Charge (%)	50
5.	Discharge current [i1, i2, i3,...] (amps)	[1.5 3]
6.	Units	Ampere-hour
7.	Battery response time (s)	30

vii. Parameters of LC filter:

Table 3.7: Parameters of LC filter

Sl. No.	Parameters	Values
1.	Branch Type	LC
2.	Inductance L (H)	2e-3
3.	Capacitance C (F)	1e-6

viii. Parameters of Three phase transformer (Star-Delta):

Table 3.8: Parameters of Three phase transformer (Star-Delta)

Sl. No.	Parameter	Values
1.	Winding 1 connection (ABC terminals)	Yg
2.	Winding 2 connection (abc terminals)	Delta (D11)

3.	Units	SI
4.	Nominal power and frequency [Pn(VA) , fn(Hz)]	[100e3 , 50]
5.	Winding 1 parameters [V1 Ph-Ph(Vrms) , R1(ohm) , L1(H)]	[11000 2.42 0.30812]
6.	Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(ohm) , L2(H)]	[400 0.0096 0.0012223]
7.	Magnetization resistance Rm (ohm)	6.05e+05
8.	Magnetization inductance Lm (H)	1925.8

ix. Parameters of Three phase Parallel RLC load of RAPS system:

Table 3.9: Parameters of Three phase Parallel RLC load of RAPS system

Sl. No.	**Parameter**	**Value**
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	100
7.	Load type	Constant Z

x. Parameters of Three phase Parallel RLC load1 of RAPS system:

Table 3.10: Parameters of Three phase Parallel RLC load1 of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	70
7.	Load type	Constant Z

xi. Parameters of Three phase Parallel RLC load2 of RAPS system:

Table 3.11: Parameters of Three phase Parallel RLC load2 of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	50
7.	Load type	Constant Z

xii. Parameters of Three phase V-I measurement2 block:

Table 3.12: Parameters of Three phase V-I measurement2 block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xiii. Parameters of Three phase V-I measurement block:

Table 3.13: Parameters of Three phase V-I measurement block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xiv. Parameters of Three phase V-I measurement1 block:

Table 3.14: Parameters of Three phase V-I measurement1 block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xv. Parameters of SVPWM generator (2-level) block:

Table 3.15: Parameters of SVPWM generator (2-level) block

Sl. No.	Parameter	Value
1.	Data type of input reference vector (Uref)	Internally generated
2.	Switching pattern	Pattern #1
3.	PWM frequency (Hz)	50

4.	Output voltage: [Mag (0<m<1), Phase (degrees), Freq (Hz)]	[0.8 0 50]
5.	Sample time	1e-6

xvi. Parameters of Capacitor:

Table 3.16: Parameters of Capacitor

Sl. No.	Parameter	Value
1.	Branch type	C
2.	Capacitance C (F)	1e-6
3.	Measurements	Branch voltage and current

xvii. Parameters of Capacitor1:

Table 3.17: Parameters of Capacitor1

Sl. No.	Parameter	Value
1.	Branch type	C
2.	Capacitance C (F)	1e-6
3.	Measurements	Branch voltage and current

xviii. Parameters of Inductor:

Table 3.18: Parameters of Inductor

Sl. No.	Parameter	Value
1.	Branch type	L

2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xix. Parameters of Inductor1:

Table 3.19: Parameters of Inductor1

Sl. No.	Parameter	Value
1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xx. Parameters of Inductor2:

Table 3.20: Parameters of Inductor2

Sl. No.	Parameter	Value
1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

3.5 SIMULINK MODEL

The Simulink model is made in MATLAB R2013a, 64 bit software and is checked for errors if present. The Simulink model is made to run or simulate in MATLAB.

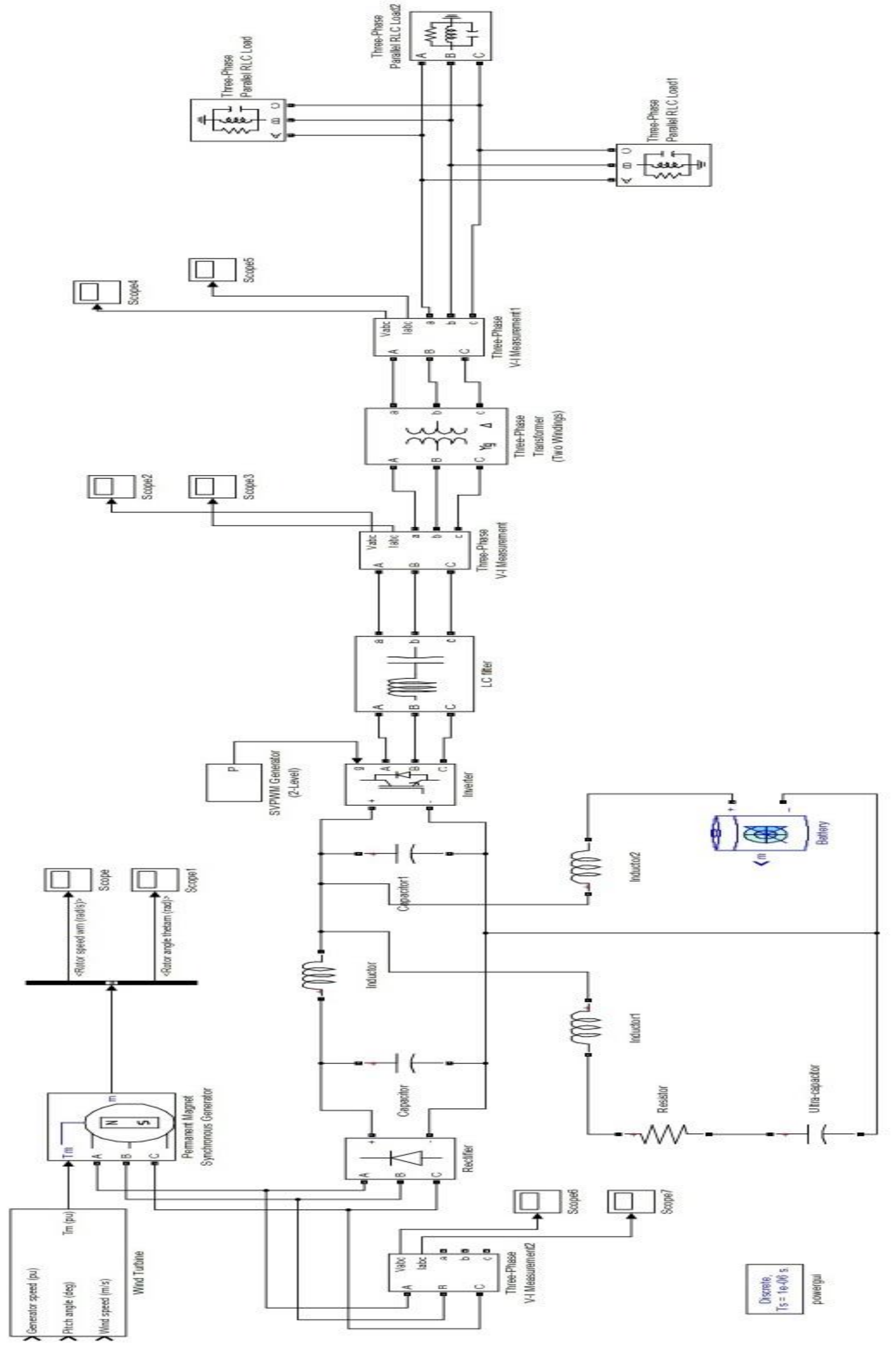

Figure 3.1: Simulink model

3.6 RESULTS

The Simulink model is made to run in MATLAB and the responses are recorded and observed.

1. **Rotor speed of PMSG in rad/sec:-**

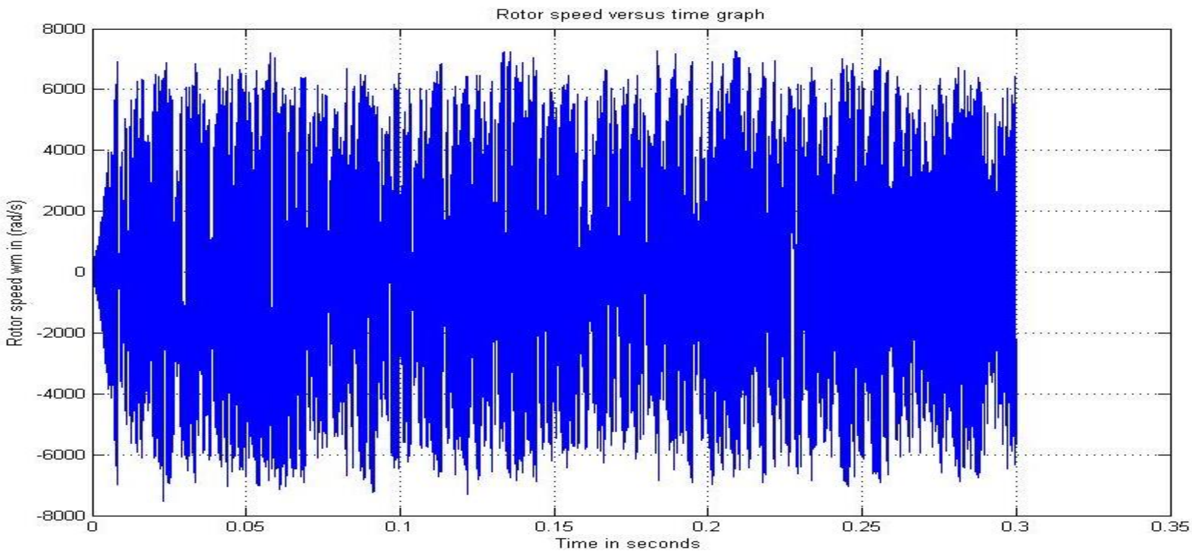

Figure 3.2: Rotor speed of PMSG in rad/sec

2. **Rotor angle of PMSG in rad:-**

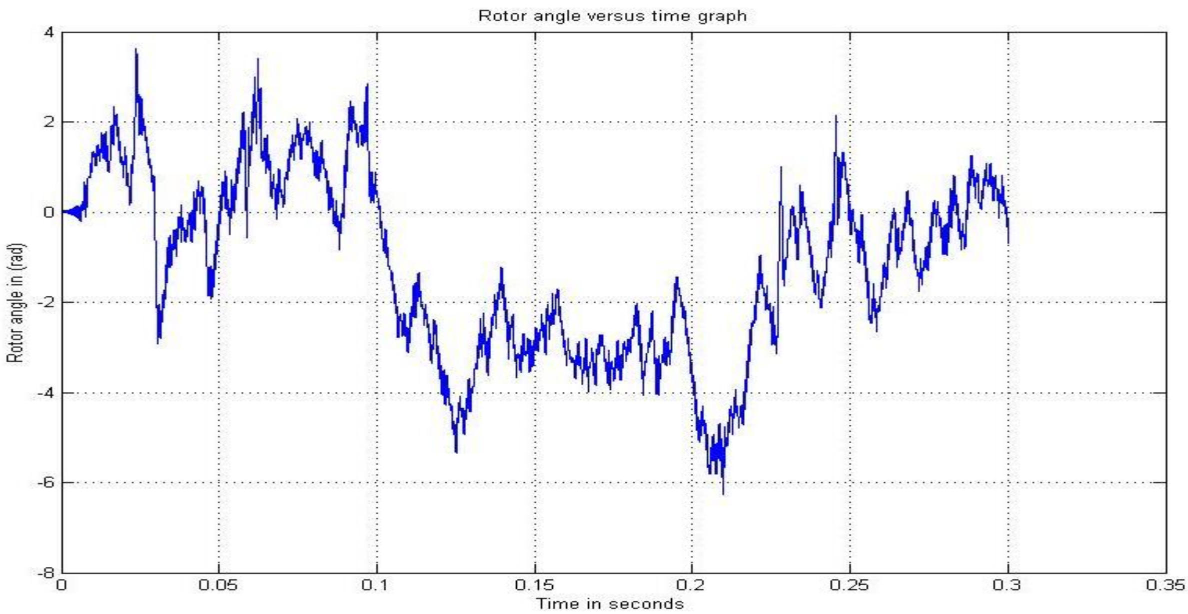

Figure 3.3: Rotor angle of PMSG in rad

3. Voltage output of PMSG:-

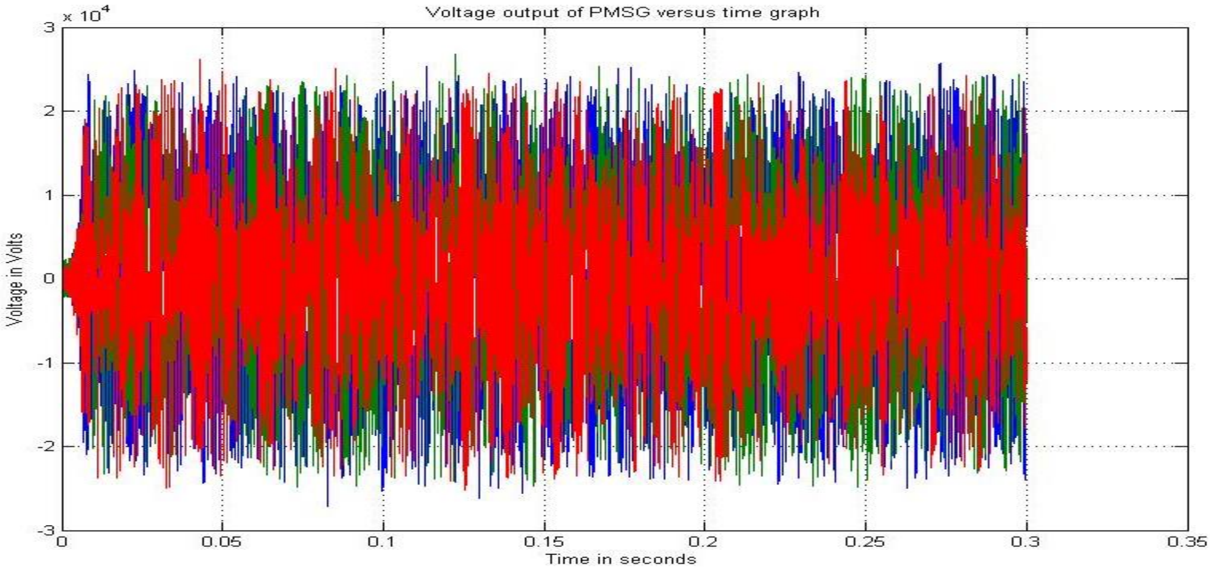

Figure 3.4: Voltage output of PMSG

The phase voltage output of the PMSG is found to be = 25383 Volts = 25.383 KV.

4. Voltage output at the inverter end:-

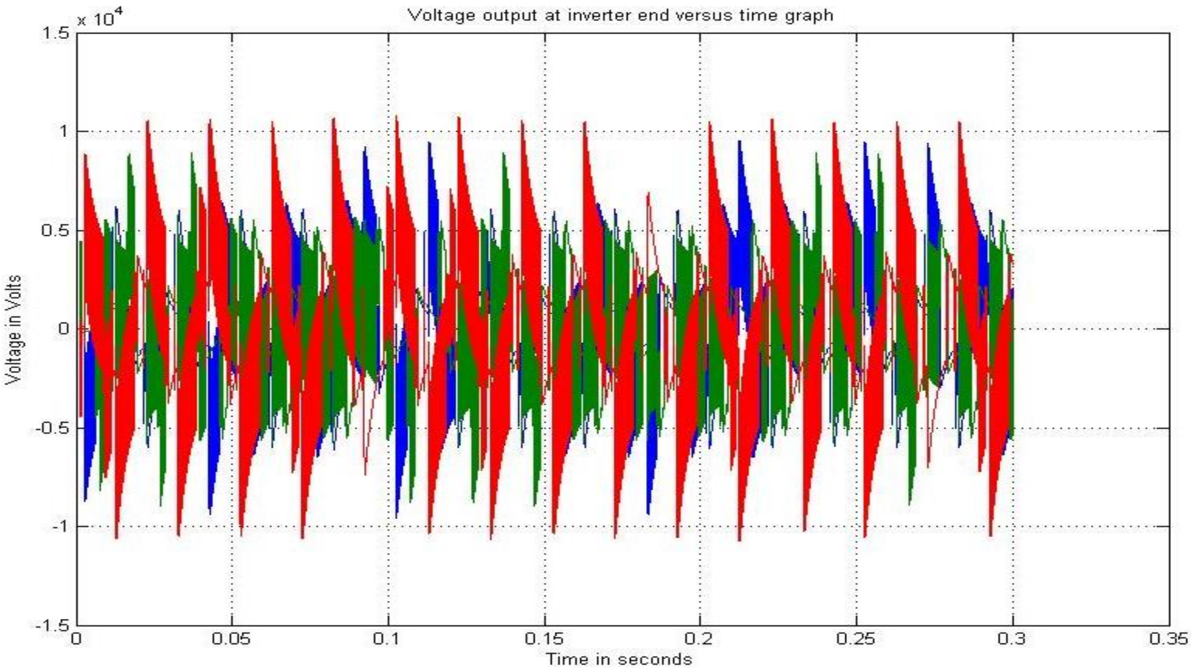

Figure 3.5: Voltage output at the inverter end

The phase voltage output at the inverter end is found to be = 10639 Volts = 10.639 KV.

5. **Current output at the inverter end:-**

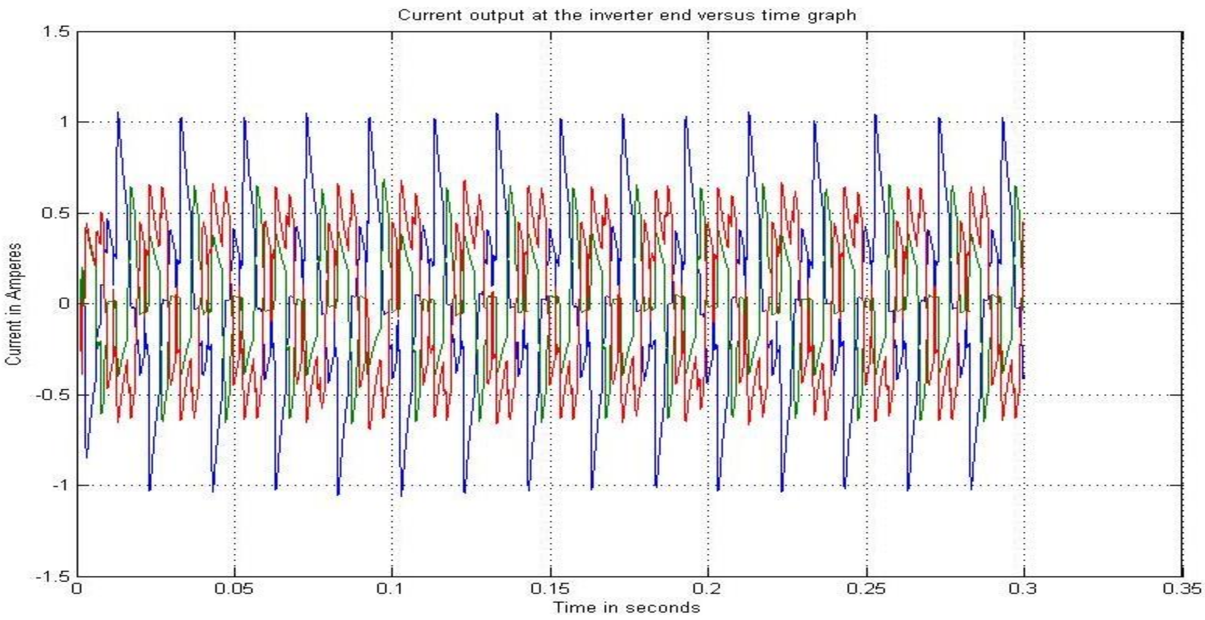

Figure 3.6: Current output at the inverter end

6. **Voltage at the load end:-**

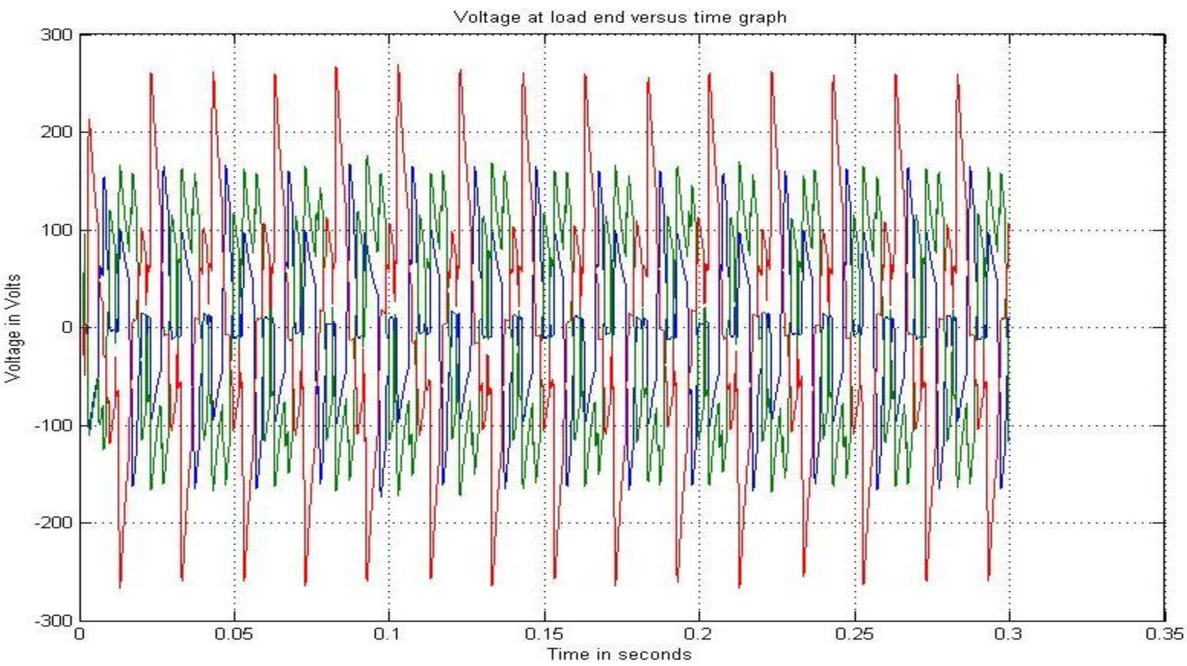

Figure 3.7: Voltage at the load end

The phase output voltage at the load end is found to be = 266 Volts.

7. **Current at the load end:-**

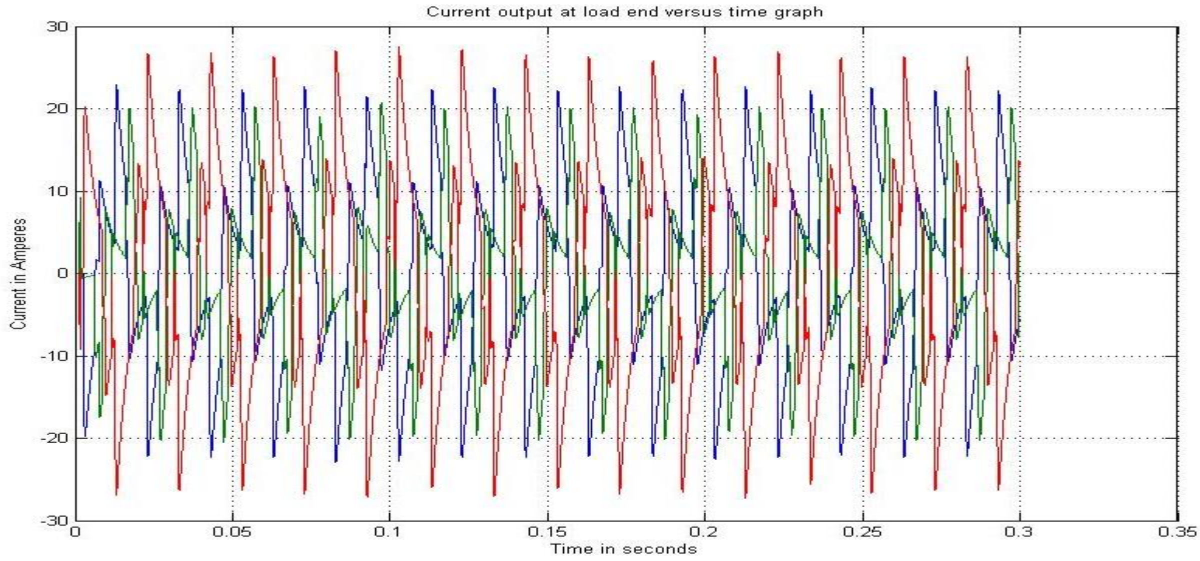

Figure 3.8: Current at the load end

8. **Voltage at load end at 10 m/sec wind speed:-**

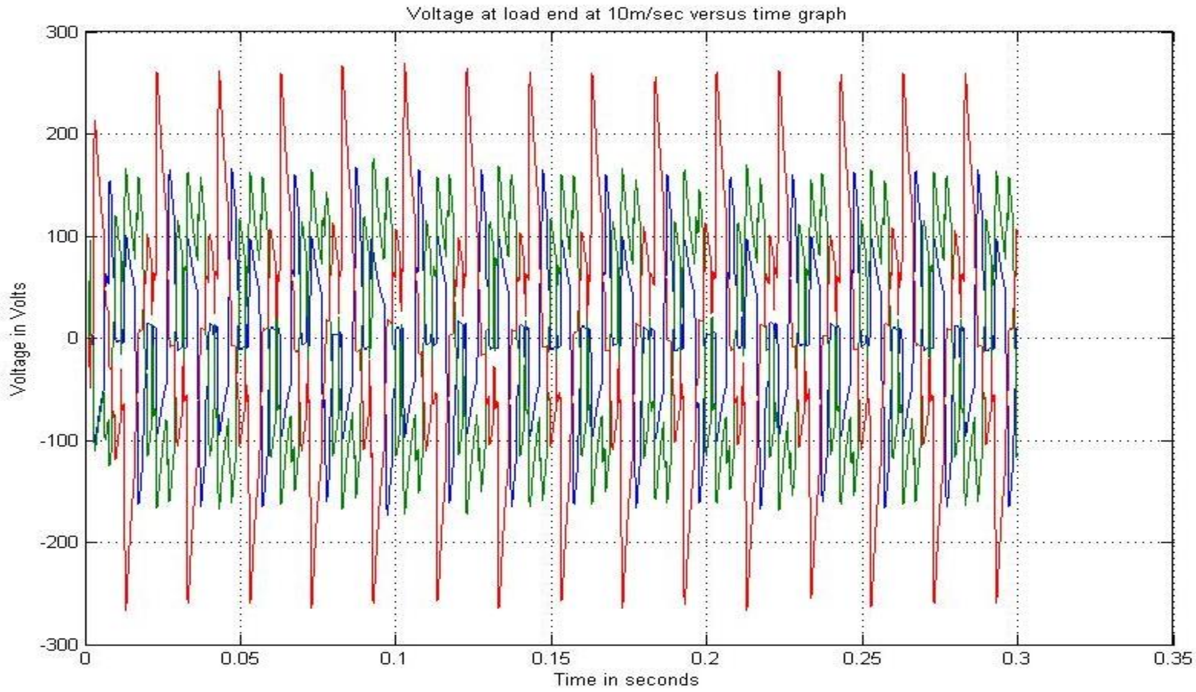

Figure 3.9: Voltage at load end at 10 m/sec wind speed

The phase output voltage at load end at 10 m/sec wind speed is found to be = 263 Volts.

9. **Voltage at load end at 8 m/sec wind speed:-**

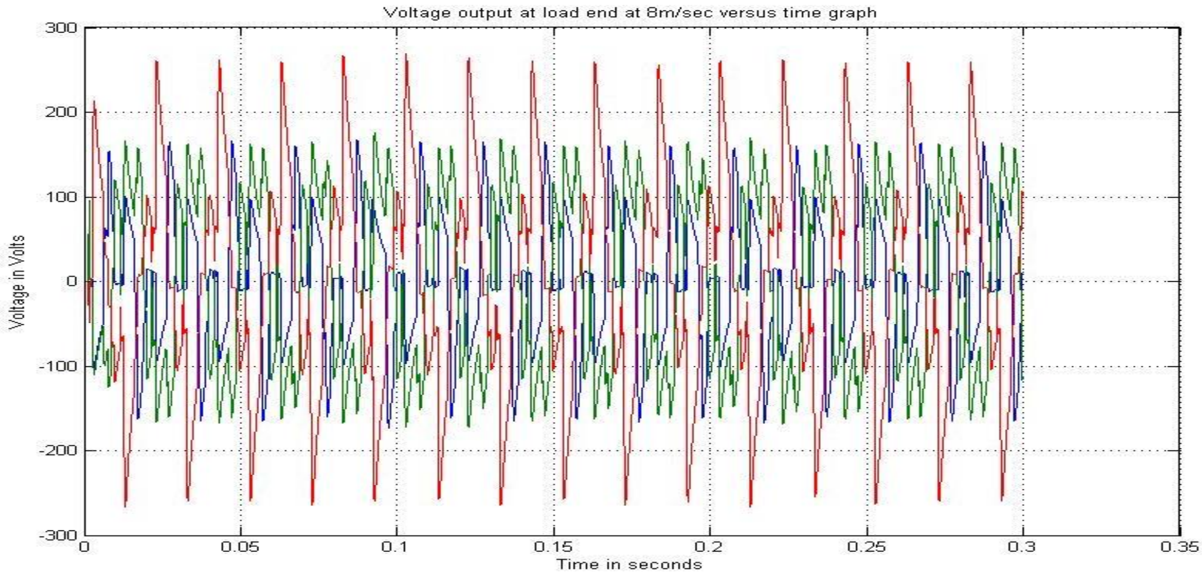

Figure 3.10: Voltage at load end at 8 m/sec wind speed

The phase output voltage at load end at 8 m/sec wind speed is found to be = 263 Volts.

10. **Voltage at load end at 5 m/sec wind speed:-**

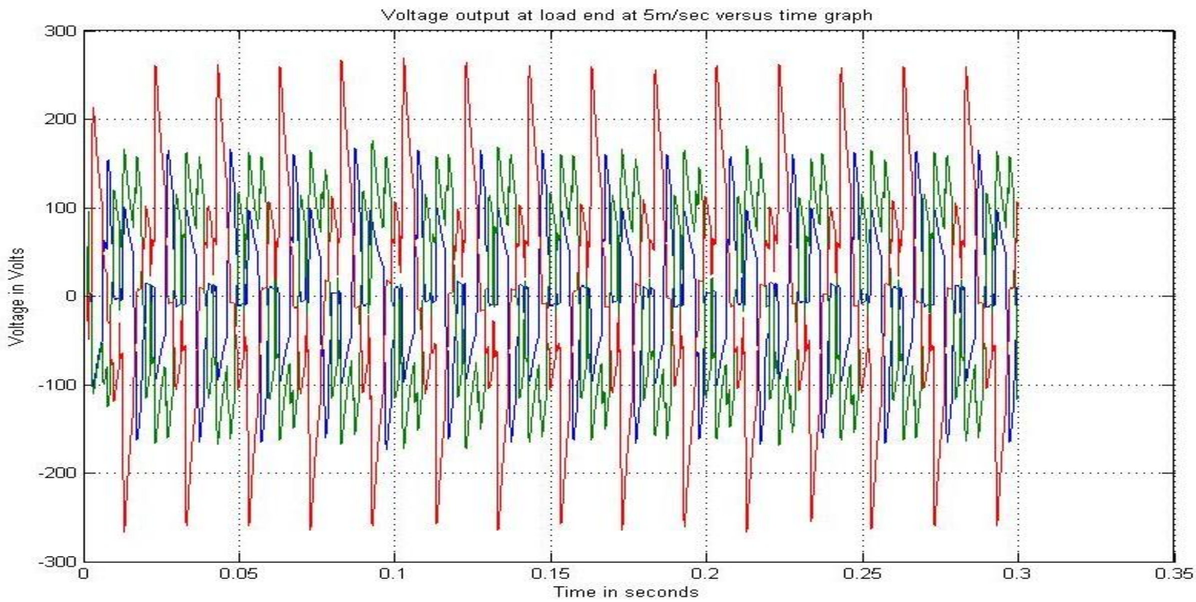

Figure 3.11: Voltage at load end at 5 m/sec wind speed

The phase output voltage at load end at 5 m/sec wind speed is found to be = 263 Volts.

3.7 CONCLUSION

The MATLAB model of Hybrid Energy Storage Systems (HESS) by using PMSG in RAPS systems is simulated and the observations are recorded and observed. The model is tested for different wind speeds at 12mt./sec, 10 mt./sec, 8 mt./sec and 5 mt./sec. The model is made to run in MATLAB and the observations are recorded and observed. The inclusion of battery and ultra-capacitors has led the RAPS systems to increase their stability. The reliability of RAPS systems has also been improved.

It has also been observed that the output voltage of PMSG is 25 KV, which is the nominal voltage required for railway electrification. So, PMSG can also be used for railway electrification purposes.

CHAPTER-4

MPPT STRATEGY FOR A PMSG BASED RAPS NETWORK USING MATLAB

4.1 INTRODUCTION

The RAPS network in rural areas has been used to supply power where the utility grid is not present or not easily available. The RER have gained popularity nowadays against conventional generators. In order to maintain the proper functioning of the RAPS network, we need to go for maximum power point tracking (MPPT) strategy. This work suggests to carry out MPPT strategy for a PMSG based RAPS network using boost converters. In MPPT, we will have to find the instances during which the network delivers the maximum power to the entire network. Boost Converters are usually DC-DC converters. It is used to step-up the voltage to a voltage which is greater than the source voltage. Here, the output voltage is always higher than the input voltage. Here, we find out the instances at which the network delivers maximum power. It will help to increase the efficiency of the network.

In order to maintain the proper functioning of the RAPS network, we need to go for maximum power point tracking (MPPT) strategy. In MPPT, we will have to find the instances during which the network delivers the maximum power to the entire network. In a PMSG based RAPS network, the wind turbine delivers the maximum power at 12 m/sec wind speed. The wind turbine block in MATLAB is a function of wind speeds and pitch angle (beta). It mainly depends on the nature and speed of the wind. According to the wind turbine power characteristics of the wind turbine in MATLAB at pitch angle beta = 0 deg., the wind turbine delivers maximum power or maximum turbine power output at 12 m/sec wind speed and at 1.2 p.u. turbine speed. The wind turbine delivers maximum power at 12 m/sec wind speed.

To carry out MPPT, we will be utilising boost converters in the mid of the dc link of the RAPS network. The boost converters consists of an inductor, a semi-conductor switch or switching device, a diode and a capacitor connected across the load. Here, we have used IGBT as the switching device in the boost converter. Boost Converters are usually DC-DC converters. They are also known as step-up converters. It is used to step-up the voltage to a voltage which is greater than the source voltage. It is used for DC to DC conversion purposes. Here, the output voltage is always higher than the input voltage. Here, we find out the instances at which the network delivers maximum power in order to carry out MPPT strategy.

4.2 WORKING PRINCIPLE

The research work has to be carried out with the help of some tools like MATLAB software, with a version, MATLAB R2013a 64 bit software. The elements like wind turbine block, PMSG (Permanent Magnet Synchronous Generator), rectifier block, diode, IGBT, pulse generator, inverter block, inductor, capacitor, 3-phase VI measurement block, LC filter block, ultra-capacitor block, battery block, 3-phase transformer, 3-phase RLC load block, etc. required in our work will be taken from "Sim power systems" tool box under "Sim scape" icon present in Simulink library of the MATLAB. The elements like From and Goto required in our work will be taken from "Signal Routing" tool under "Simulink" icon present in Simulink library of the MATLAB. "Battery" and "Ultra-capacitors" block is utilised for hybrid energy storage systems for maintaining the power supply in the network or RAPS systems and improving the stability and reliability of the network. "Powergui" block is used as a generator to the model in order to make it run in MATLAB. "Scope" and "Workspace" block is also utilised under "Sink" icon present in Simulink library of the MATLAB in order to record the observations or responses after simulating the model. The model is made to run at 50 Hz frequency. First of all, all the blocks are initialized as per requirements and then the model is made to run to check if there are errors present in it or not. Then the Simulink model is made to run or simulate by using MATLAB R2013a 64 bit software tool. The responses are observed by the help of scope or workspace.

The HESS (UCs and Lithium-ion battery), is interfaced into a PMSG based WECS. First of all, the wind turbine rotates to generate the mechanical torque. Then, the torque is given as input to the PMSG. PMSG is used to convert the mechanical work done by the wind turbine to electrical energy. The output voltage of PMSG is given as input to the diode bridge rectifier. The diode bridge rectifier converts the input sinusoidal alternating voltage to the DC voltage and passes on to the associated network. The DC voltage is converted to alternating voltage by means of an IGBT/ diode based inverter. The energy storage devices, i.e., UCs and lithium-ion batteries are connected to the DC side, which is in between the rectifier and inverter end. It acts as a branch in between the rectifier and inverter end. In between the rectifier and the inverter end, the boost converter is inserted in the mid of the dc link. The boost converter comprises of an inductor, IGBT switching device, a diode and a capacitor connected across the dc link. The boost converter is used here to carry out the maximum power point tracking (MPPT) strategy in order to deliver the maximum power to the entire network. The output power generation through IGBT/ diode bridge inverter is then made to pass through a three phase transformer by connecting a LC-filter in between them. The output is then provided further to the RAPS network system. The "From" and "Goto" are used to find out the power at the rectifier end, inverter end and at the load end.

4.3 COMPONENTS

The components present in this work are as follows:-

i. Wind turbine.
ii. Permanent Magnet Synchronous Generator (PMSG).
iii. Ultra-Capacitors.
iv. Batteries.
v. Boost Converters.

i. Wind Turbine:

A wind turbine also known as wind energy converter, is used to convert the wind's kinetic energy to electrical energy. A wind turbine consists of a turbine which is rotated by means of wind. The wind acts as an input to the wind turbine. The wind turbine is used to generate the mechanical torque, which is then taken as an input to get the electrical energy. The wind turbine has 2 different types of axis-vertical axis and horizontal axis. The smallest of all the wind turbines are used for providing power to traffic warning signs and charging of battery of boats. The turbines can rotate in horizontal axis manner or vertical axis manner. The horizontal axis is the older one and the most common one. The wind turbines mostly have a gearbox. The wind turbines are mostly used for production of electric power commercially.

ii. Permanent Magnet Synchronous Generator (PMSG):

PMSG stands for permanent magnet synchronous generator. It is a type of generator where the permanent magnet provides the excitation field. The term synchronous refers to the fact that the rotor and stator rotate with the same speed, and permanent magnet generates the magnetic field and current gets induced into the armature.

In PMSG, the "rotor" is the permanent magnet, and the "stator" is the armature, which is connected to the load end. Both the stator and the rotor maintain their synchronism with respect to their rotation. The rotor i.e. permanent magnet of the PMSG rotates due to the input given as mechanical torque by the wind turbine. The movement of permanent magnet leads to generate flux which in turn leads to generate the emf and finally leads to generate the voltage at the armature windings. The output voltages of PMSG consists of three phase voltages, which are phase shifted to each other by an angle of 120 degrees. The stator winding of the PMSG carries the three phase armature windings and are electrically displaced by 120 degrees from each other producing an ac voltage output.

iii. Ultra-Capacitors:

An ultra-capacitor is known as super-capacitor. It is an electrical component capable of holding electrical charge hundreds of times than a standard capacitor. It is useful in devices which require low current and low voltage. They are normally used in emergency radios and flashlights.

The UC requires charging before its mode of operation. Once the UC is fully charged, it can function for some period of time till it gets fully discharged or it requires charging. Once it is fully charged, then current stops flowing and the UCs output voltage is equal to the voltage of the supply. A fully charged UC will store energy till it gets fully discharged. When the UC is in discharging mode, then the stored energy gets converted into electrical energy to supply to the load present within the network. UCs are always connected in parallel manner with the network. UCs comprises of a very high value of capacitor and very less value of resistor connected in series manner. A high value of capacitor and less value of resistor are connected in series manner and the whole arrangement is connected in parallel with the circuit or the network. It always contains very high value of capacitance.

iv. Batteries:

A battery consists of one or more electro-chemical cells, which are connected to provide power to the devices like flashlights, smartphones, etc., In MATLAB, the battery (mask) is present, in which different types of batteries are found, which are connected in series with the circuit. There are many different types of batteries in MATLAB. Any one type of battery can be chosen at a time. Here, we have used lithium-ion battery.

v. Boost Converters:

Boost Converters are usually DC-DC converters. They are also known as step-up converters. It is used to step-up the voltage to a voltage which is greater than the source voltage. It is used for DC to DC conversion purposes. Here, the output voltage is always higher than the input voltage.

It consists of an inductor, a semi-conductor switch or switching device, a diode and a capacitor connected across the load. The switching device may be an IGBT, MOSFET or BJT. Here, we have taken the switching device as IGBT. The boost converters have high efficiency. Here, when the switch or switching device is closed, the current flows through the inductor branch and the inductor stores some energy by generating a magnetic field. When the switch is open, current gets reduced and the magnetic field previously created gets destroyed to maintain current towards the load. At this point, a higher voltage comes into account to charge the capacitor through the diode. Hence, a higher voltage comes into action which is greater than the source voltage.

4.4 PARAMETERS TAKEN

i. Parameters of Wind Turbine:

Table 4.1: Parameters of wind turbine

Sl. No.	Parameter	Value
1.	Nominal mechanical output power (W)	1.5e6
2.	Base power of the electrical generator (VA)	1.5e6/0.9
3.	Base wind speed (m/s)	12
4.	Maximum power at base wind speed (pu of nominal mechanical power)	0.73
5.	Base rotational speed (p.u. of base generator speed)	1.2
6.	Pitch angle beta to display wind-turbine power characteristics (beta >=0) (deg)	0

ii. Parameters of PMSG:

Table 4.2: Parameters of PMSG

Sl. No.	Parameters	Values

1.	Number of phases	3
2.	Back EMF waveform	Sinusoidal
3.	Rotor type	Round
4.	Mechanical input	Torque Tm
5.	Preset model	No
6.	Stator phase resistance Rs (ohm)	0.425
7.	Armature inductance (H)	8.35e-3
8.	Flux linkage established by magnets (V.s)	1.225
9.	Inertia, viscous damping, pole pairs, static friction [J(kg.m^2) F(N.m.s) p() Tf(N.m)]	[2.26e-5 1.35e-5 10 0]
10.	Initial conditions [wm(rad/s) thetam(deg) ia,ib(A)]	[0,0, 12,12]
11.	Sample time	-1
12.	Rotor flux position when theta = 0	90 degrees behind phase A axis (modified park)

iii. Parameters of Diode bridge Rectifier:

Table 4.3: Parameters of Diode bridge Rectifier

Sl. No.	Parameter	Value
1.	Number of bridge arms	3
2.	Snubber resistance Rs (Ohms)	5e-3
3.	Snubber capacitance Cs (F)	1e-6
4.	Power Electronic device	Diodes

5.	Ron (Ohms)	3
6.	Lon (H)	0
7.	Forward voltage Vf (V)	11e3

iv. Parameters of IGBT/ Diode bridge inverter:

Table 4.4: Parameters of IGBT/ Diode bridge inverter

Sl. No.	Parameter	Value
1.	Number of bridge arms	3
2.	Snubber resistance Rs (Ohms)	5
3.	Snubber capacitance Cs (F)	1e-6
4.	Power Electronic device	IGBT/ Diodes
5.	Ron (Ohms)	3
6.	Forward voltages [Device Vf(V) , Diode Vfd(V)]	[11e3 0.7]
7.	[Tf (s) , Tt (s)]	[1e-6 2e-6]

v. Parameters of Ultra-Capacitors (UCs):

Table 4.5: Parameters of Ultra-Capacitors (UCs)

Sl. No.	Parameter	Value
1.	Resistance R (Ohms)	2e-3
2.	Capacitance C (F)	150

vi. Parameters of Batteries:

Table 4.6: Parameters of Batteries

Sl. No.	Parameter	Value
1.	Battery type	Lithium-Ion
2.	Nominal Voltage (V)	1.2
3.	Rated Capacity (Ah)	1.5
4.	Initial State-Of-Charge (%)	50
5.	Discharge current [i1, i2, i3,...] (amps)	[1.5 3]
6.	Units	Ampere-hour
7.	Battery response time (s)	30

vii. Parameters of LC filter:

Table 4.7: Parameters of LC filter

Sl. No.	Parameters	Values
1.	Branch Type	LC
2.	Inductance L (H)	2e-3
3.	Capacitance C (F)	1e-6

viii. Parameters of Three phase transformer (Star-Delta):

Table 4.8: Parameters of Three phase transformer (Star-Delta)

Sl. No.	Parameter	Values
1.	Winding 1 connection (ABC terminals)	Yg
2.	Winding 2 connection (abc terminals)	Delta (D11)

3.	Units	SI
4.	Nominal power and frequency [Pn(VA) , fn(Hz)]	[100e3 , 50]
5.	Winding 1 parameters [V1 Ph-Ph(Vrms) , R1(ohm) , L1(H)]	[11000 2.42 0.30812]
6.	Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(ohm) , L2(H)]	[400 0.0096 0.0012223]
7.	Magnetization resistance Rm (ohm)	6.05e+05
8.	Magnetization inductance Lm (H)	1925.8

ix. Parameters of Three phase Parallel RLC load of RAPS system:

Table 4.9: Parameters of Three phase Parallel RLC load of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	100
7.	Load type	Constant Z

x. Parameters of Three phase Parallel RLC load1 of RAPS system:

Table 4.10: Parameters of Three phase Parallel RLC load1 of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	70
7.	Load type	Constant Z

xi. Parameters of Three phase Parallel RLC load2 of RAPS system:

Table 4.11: Parameters of Three phase Parallel RLC load2 of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	50
7.	Load type	Constant Z

xii. Parameters of Three phase V-I measurement2 block:

Table 4.12: Parameters of Three phase V-I measurement2 block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xiii. Parameters of Three phase V-I measurement block:

Table 4.13: Parameters of Three phase V-I measurement block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xiv. Parameters of Three phase V-I measurement1 block:

Table 4.14: Parameters of Three phase V-I measurement1 block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xv. Parameters of SVPWM generator (2-level) block:

Table 4.15: Parameters of SVPWM generator (2-level) block

Sl. No.	Parameter	Value
1.	Data type of input reference vector (Uref)	Internally generated
2.	Switching pattern	Pattern #1
3.	PWM frequency (Hz)	50

4.	Output voltage: [Mag (0<m<1), Phase (degrees), Freq (Hz)]	[0.8 0 50]
5.	Sample time	1e-6

xvi. Parameters of Capacitor:

Table 4.16: Parameters of Capacitor

Sl. No.	Parameter	Value
1.	Branch type	C
2.	Capacitance C (F)	1e-6
3.	Measurements	Branch voltage and current

xvii. Parameters of Capacitor1:

Table 4.17: Parameters of Capacitor1

Sl. No.	Parameter	Value
1.	Branch type	C
2.	Capacitance C (F)	1e-6
3.	Measurements	Branch voltage and current

xviii. Parameters of Inductor:

Table 4.18: Parameters of Inductor

Sl. No.	Parameter	Value
1.	Branch type	L

2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xix. Parameters of Inductor1:

Table 4.19: Parameters of Inductor1

Sl. No.	Parameter	Value
1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xx. Parameters of Inductor2:

Table 4.20: Parameters of Inductor2

Sl. No.	Parameter	Value
1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xxi. Parameters of Diode:

Table 4.21: Parameters of Diode

Sl. No.	Parameter	Value
1.	Resistance Ron (Ohms)	0.001
2.	Inductance Lon (H)	0
3.	Forward voltage Vf (V)	0.8

4.	Initial current Ic (A)	0
5.	Snubber resistance Rs (Ohms)	500
6.	Snubber capacitance Cs (F)	250e-9

xxii. Parameters of IGBT:

Table 4.22: Parameters of IGBT

Sl. No.	Parameter	Value
1.	Internal resistance Ron (Ohms)	1e-3
2.	Snubber resistance Rs (Ohms)	1e5
3.	Snubber capacitance Cs (F)	5e-6

xxiii. Parameters of Pulse Generator:

Table 4.23: Parameters of Pulse Generator

Sl. No.	Parameter	Value
1.	Pulse Type	Time based
2.	Time (t)	Use simulation time
3.	Amplitude	1
4.	Period (secs)	10
5.	Pulse Width (% of period)	5
6.	Phase delay (secs)	0

4.5 SIMULINK MODEL

The Simulink model is made in MATLAB R2013a, 64 bit software and is checked for errors if present. The Simulink model is made to run or simulate in MATLAB.

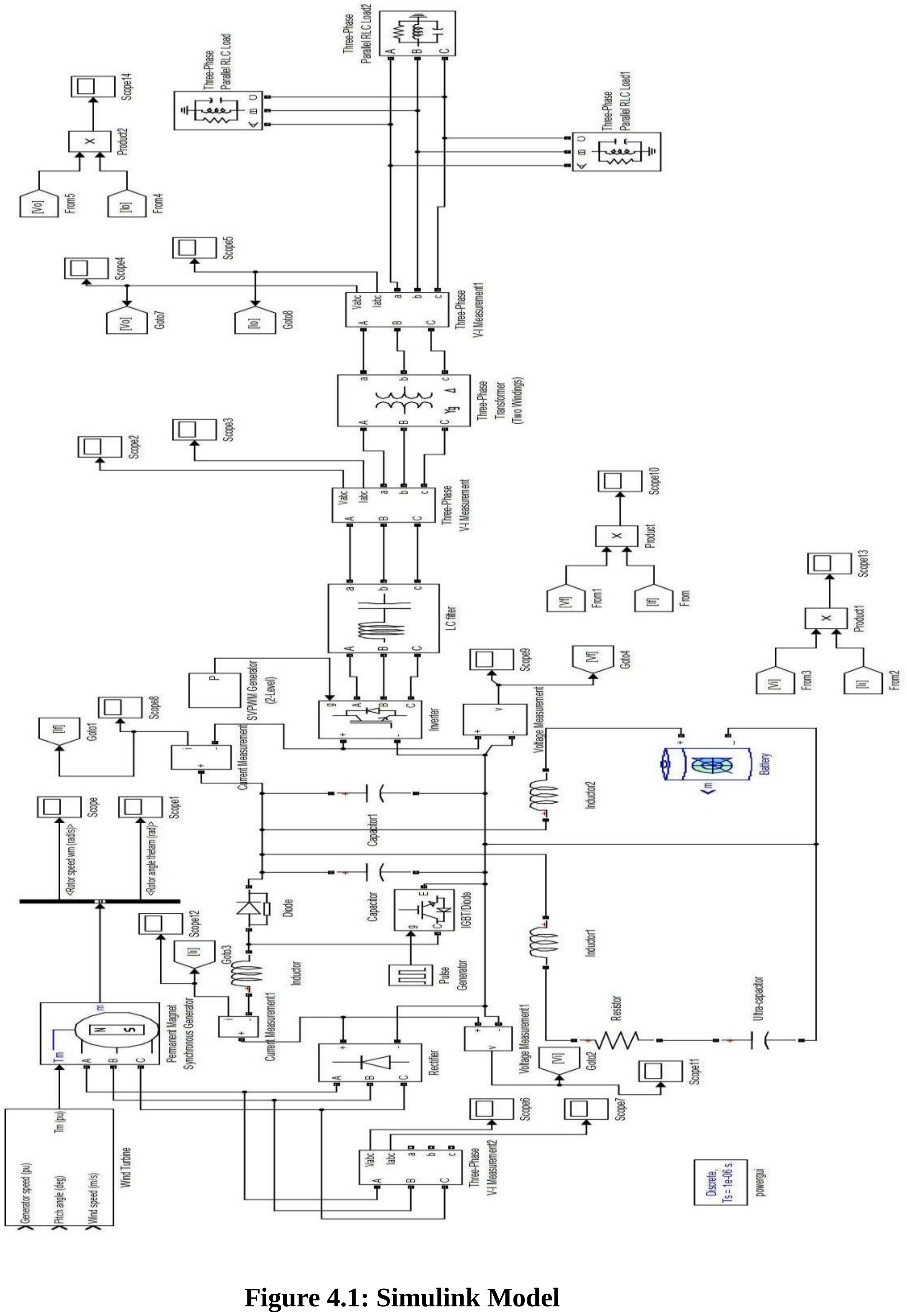

Figure 4.1: Simulink Model

4.6 RESULTS

The Simulation or MATLAB model is made to run in MATLAB and the responses are recorded and observed.

1. **Output Voltage of PMSG:-**

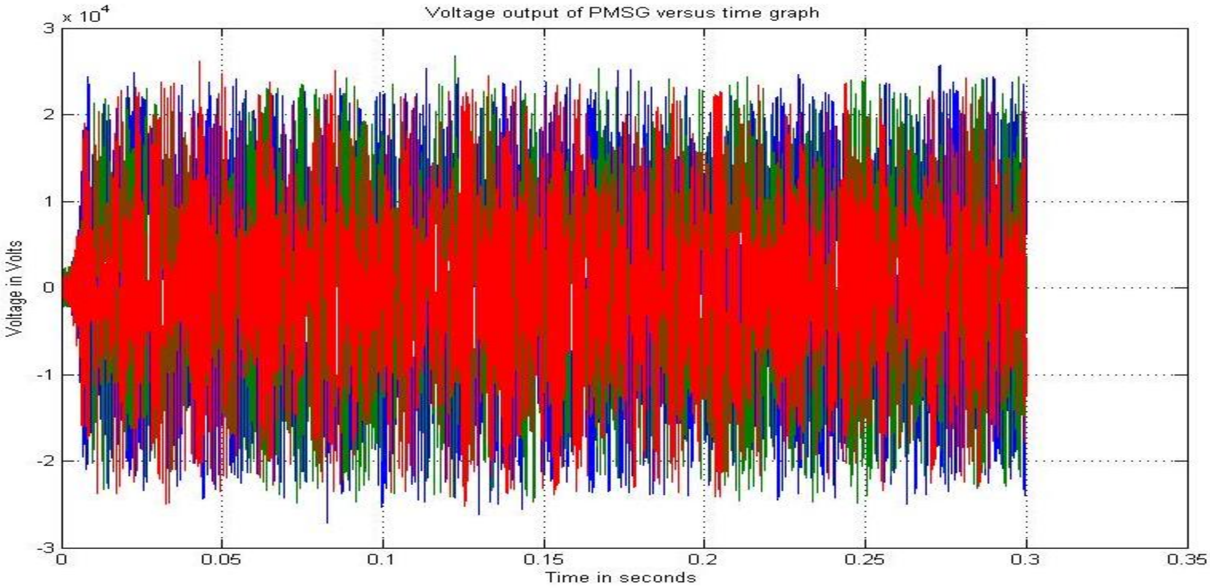

Figure 4.2: Output Voltage of PMSG

The phase voltage output of the PMSG is found to be = 25383 Volts = 25.383 KV.

2. **Voltage at the rectifier end:-** Voltage = 6658 Volts

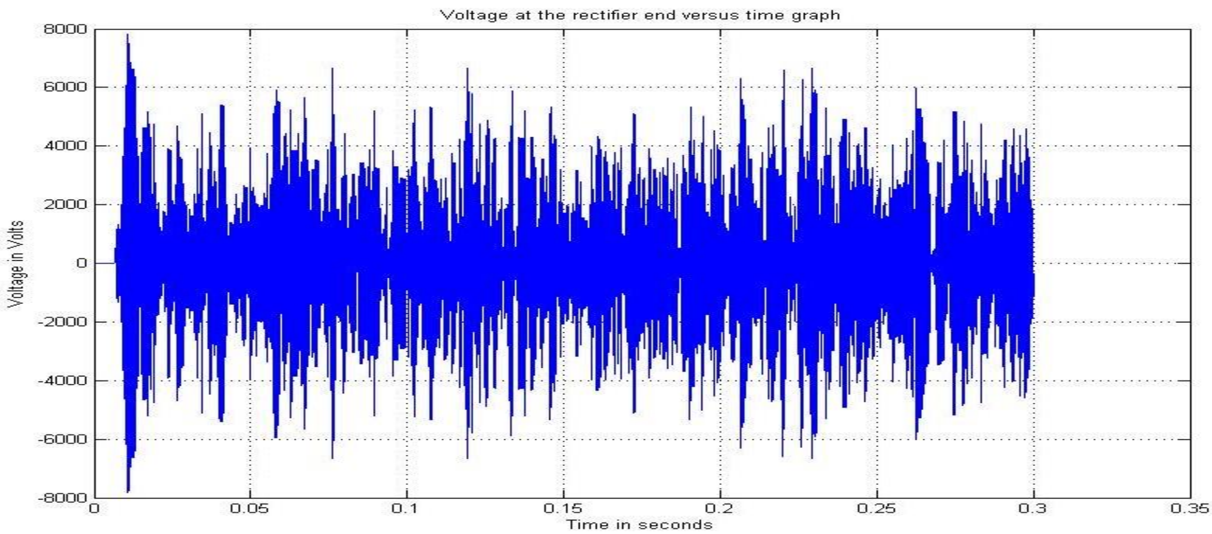

Figure 4.3: Voltage at the rectifier end

The voltage at the rectifier end is found to be = 6658 Volts.

3. **Current at the rectifier end:-** Current = 279 A

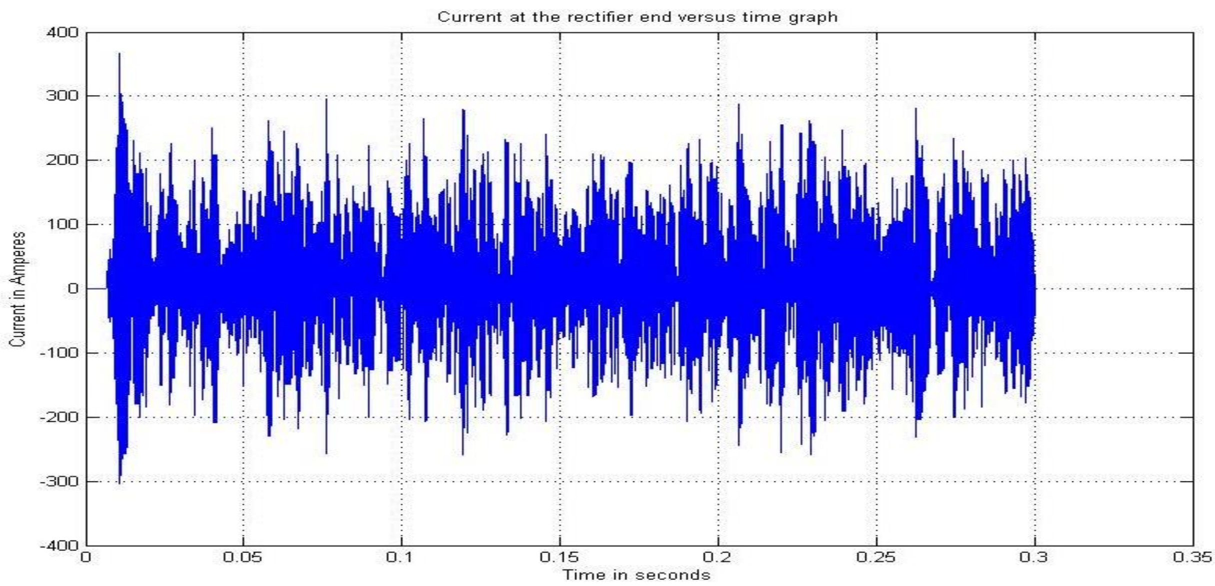

Figure 4.4: Current at the rectifier end

The Current at the rectifier end is found to be = 279 A.

4. **Power at the rectifier end:-** Power = $8.57 * 10^5$ Watts

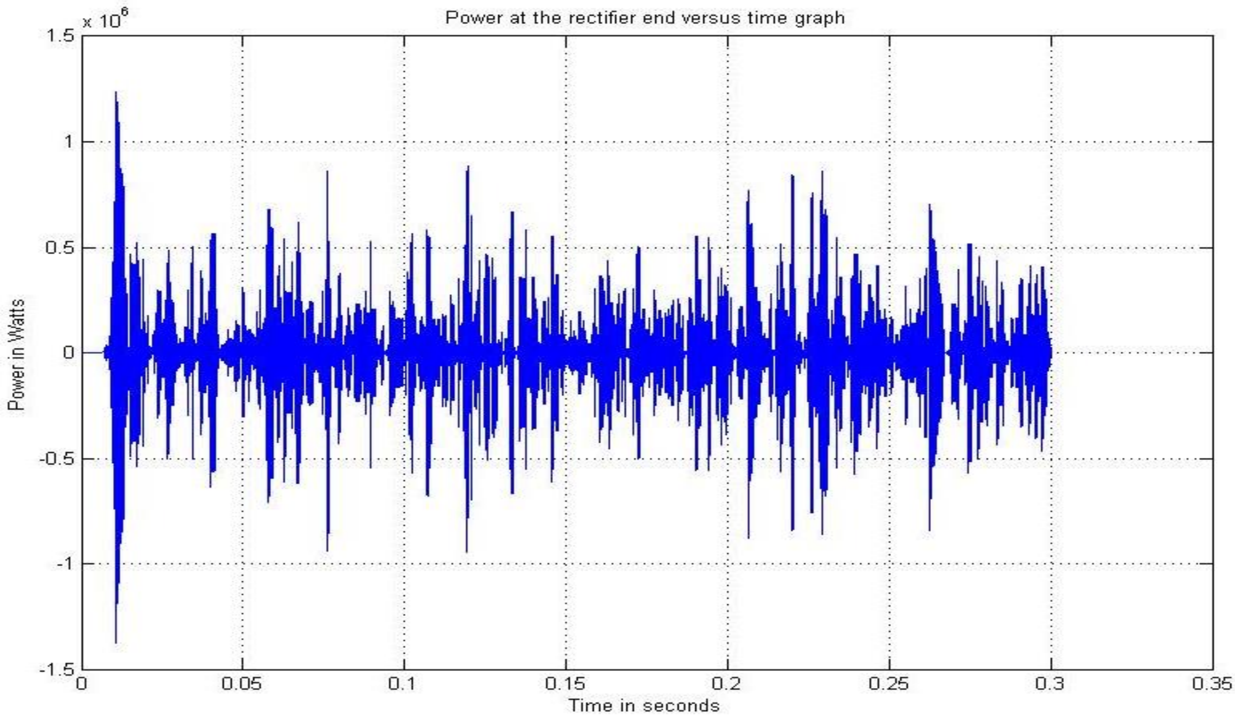

Figure 4.5: Power at the rectifier end

Here, power is found to be maximum at = $1.235 * 10^6$ Watts at 0.0106 sec.

5. **Current at the inverter end:-** Current = 1440 A

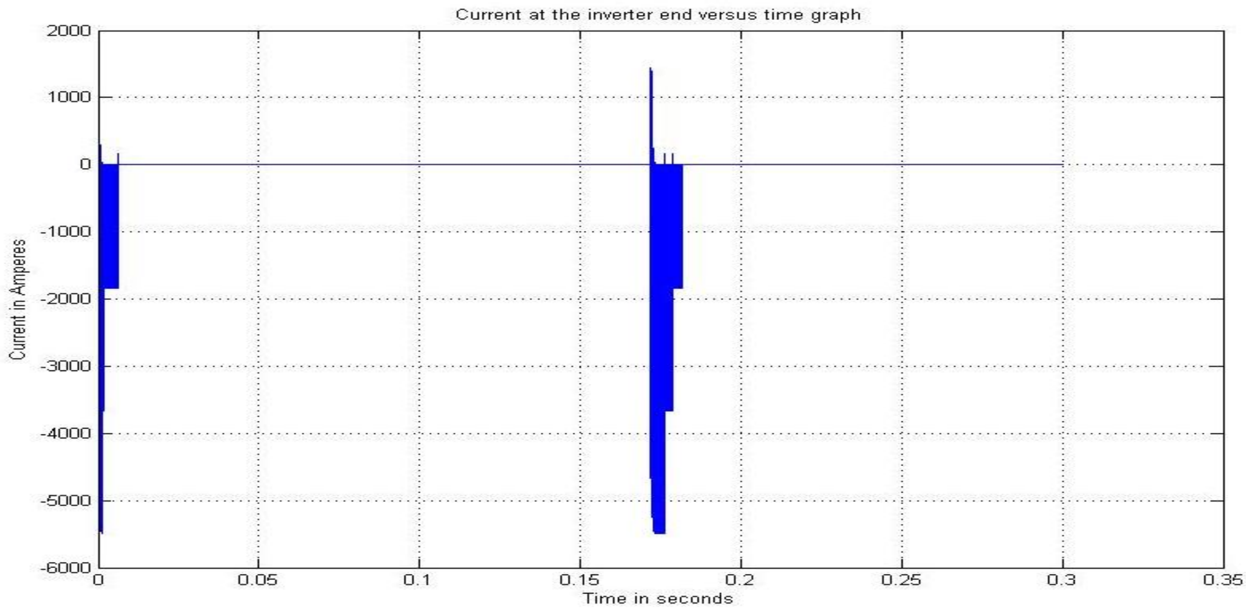

Figure 4.6: Current at the inverter end

The current at the inverter end is found to be = 1440 A.

6. **Voltage at the inverter end:-** Voltage = 5507 Volts

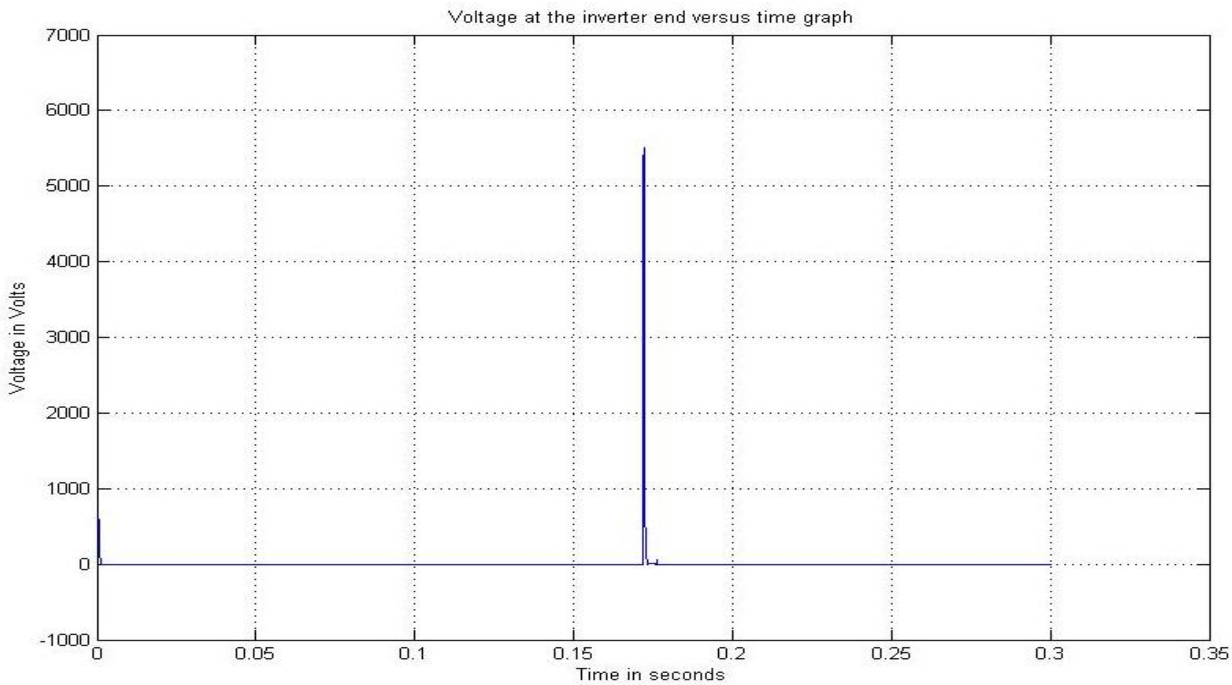

Figure 4.7: Voltage at the inverter end

The Voltage at the inverter end is found to be = 5507 Volts

7. **Power at the inverter end:-** Power = $7.48*10^6$ Watts at 0.172 sec

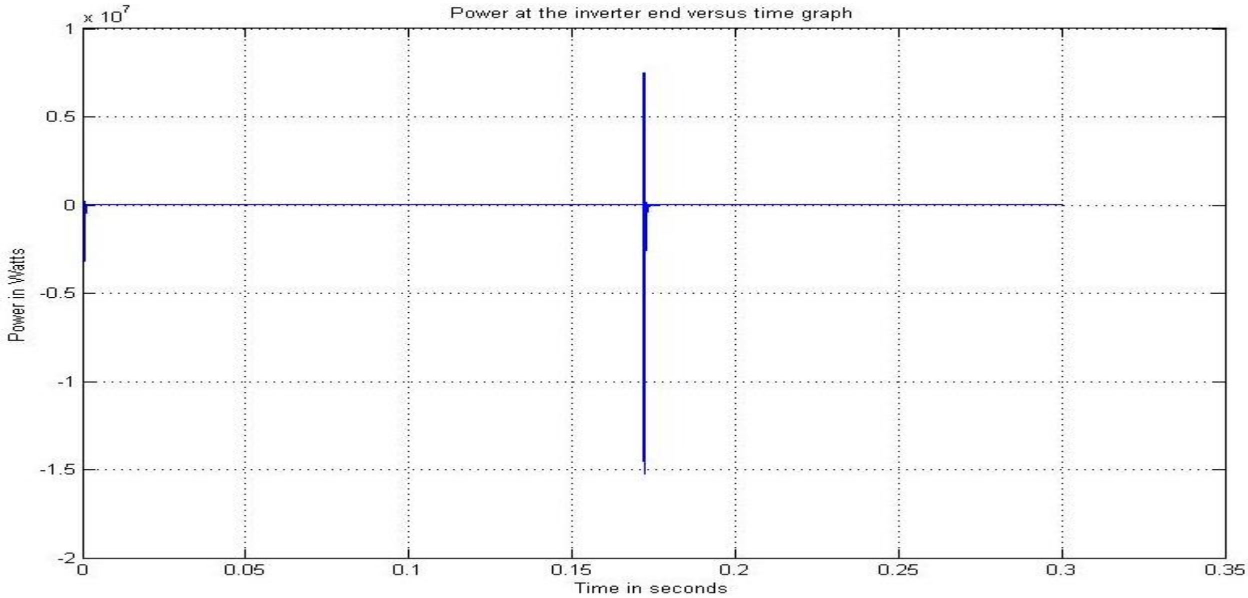

Figure 4.8: Power at the inverter end

Here, power is found to be maximum at = $7.48*10^6$ Watts at 0.172 sec.

8. **Voltage output at the inverter end:-** Voltage = 8802 Volts

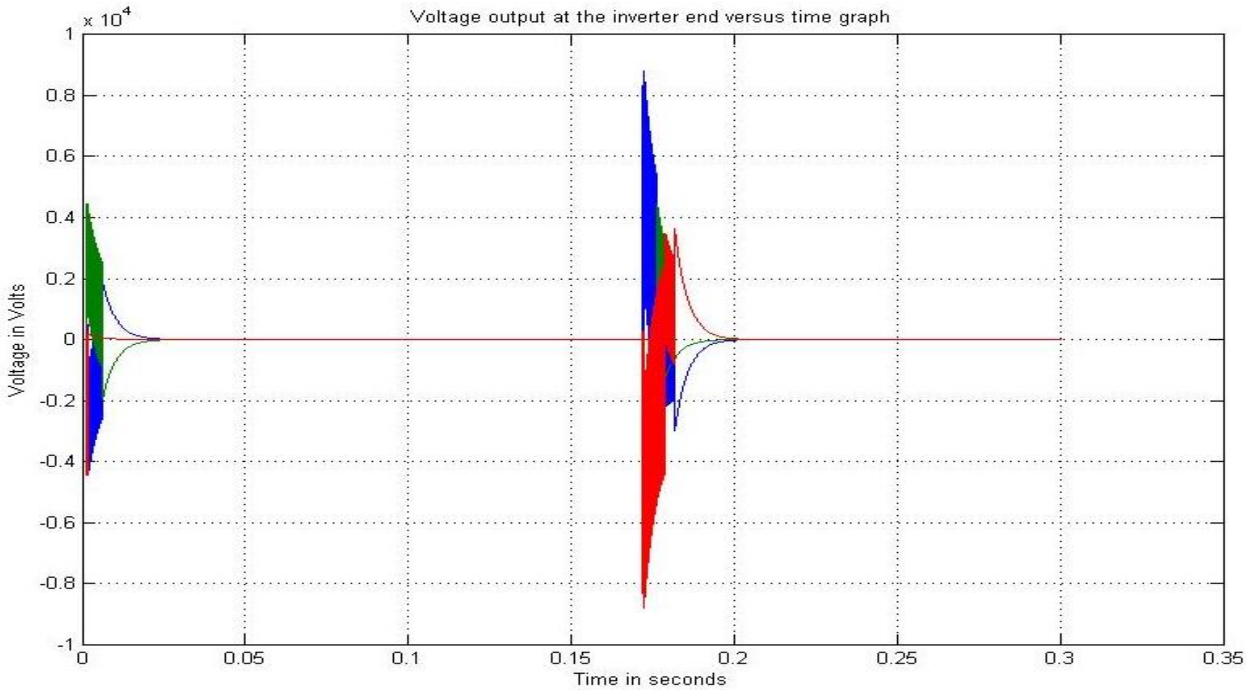

Figure 4.9: Voltage output at the inverter end

The Voltage output at the inverter end is found to be = 8802 Volts.

9. Current output at the inverter end:- Current = 0.84 A

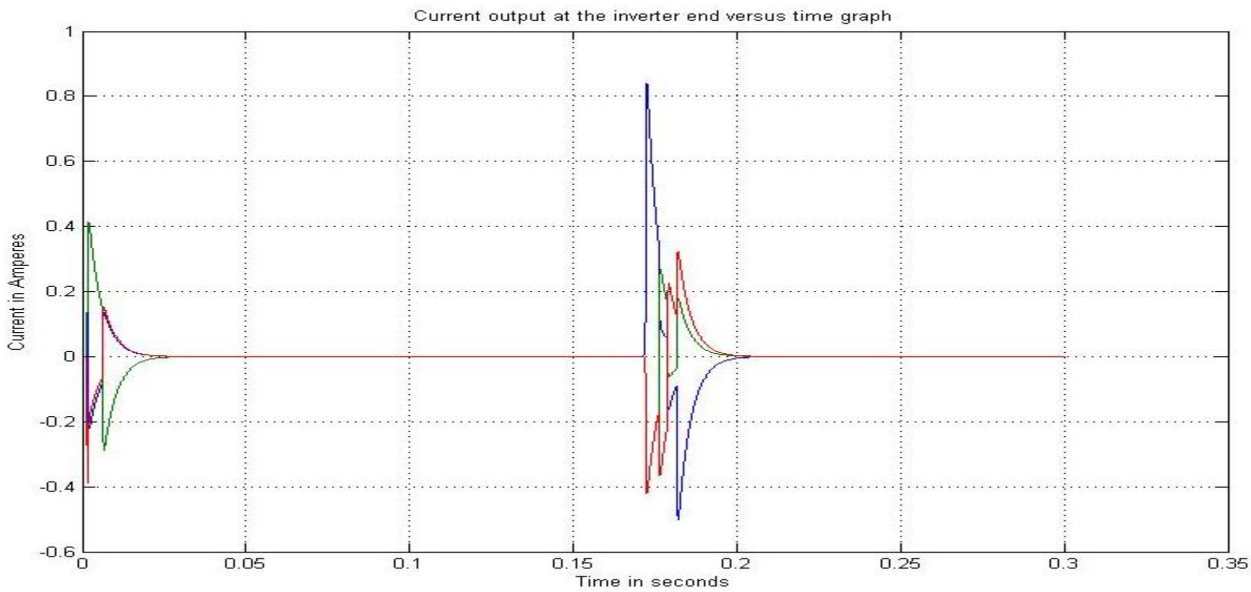

Figure 4.10: Current output at the inverter end

The Current output at the inverter end is found to be = 0.84 A.

10. Voltage at the load end:- Voltage = 128.95 Volts

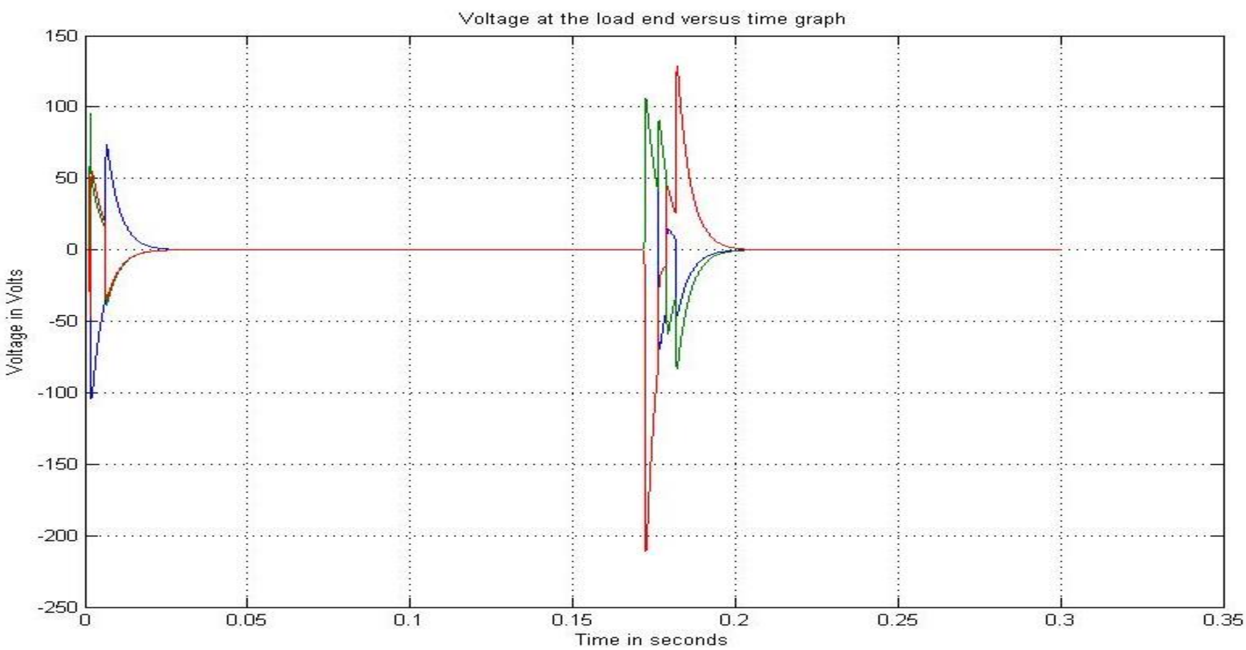

Figure 4.11: Voltage at the load end

The Voltage at the load end is found to be = 128.95 Volts.

11. Current at the load end:- Current = 20 A

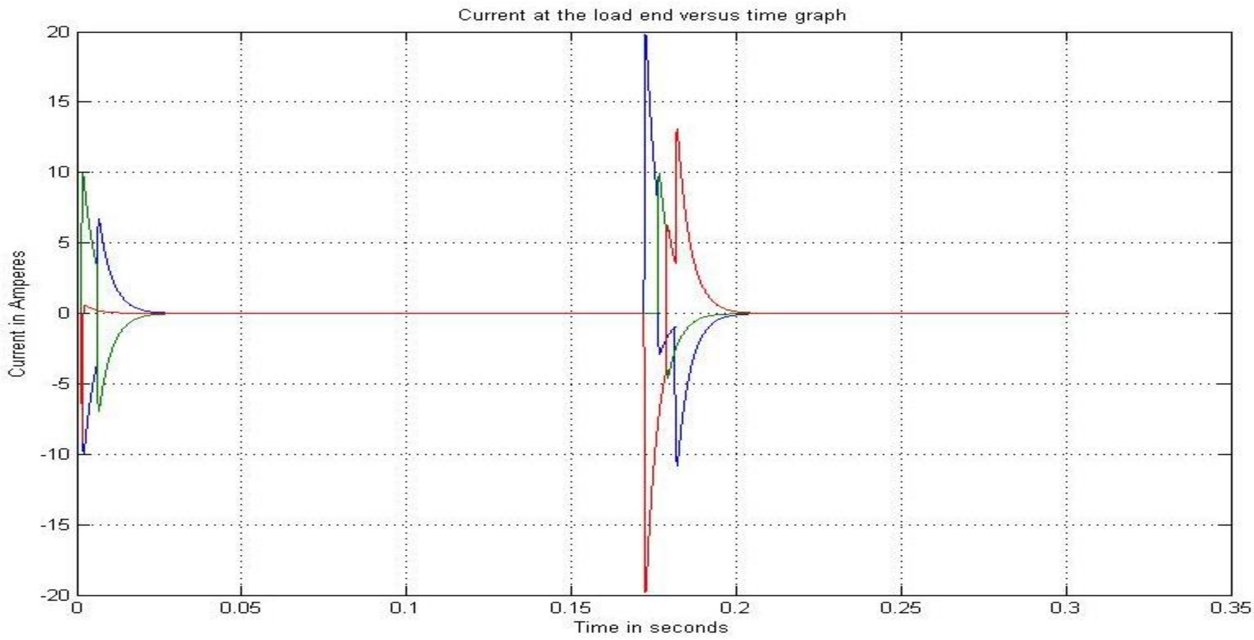

Figure 4.12: Current at the load end

The Current at the load end is found to be = 20 A.

12. Power at the load end:- Power = 4186 Watts at 0.1725

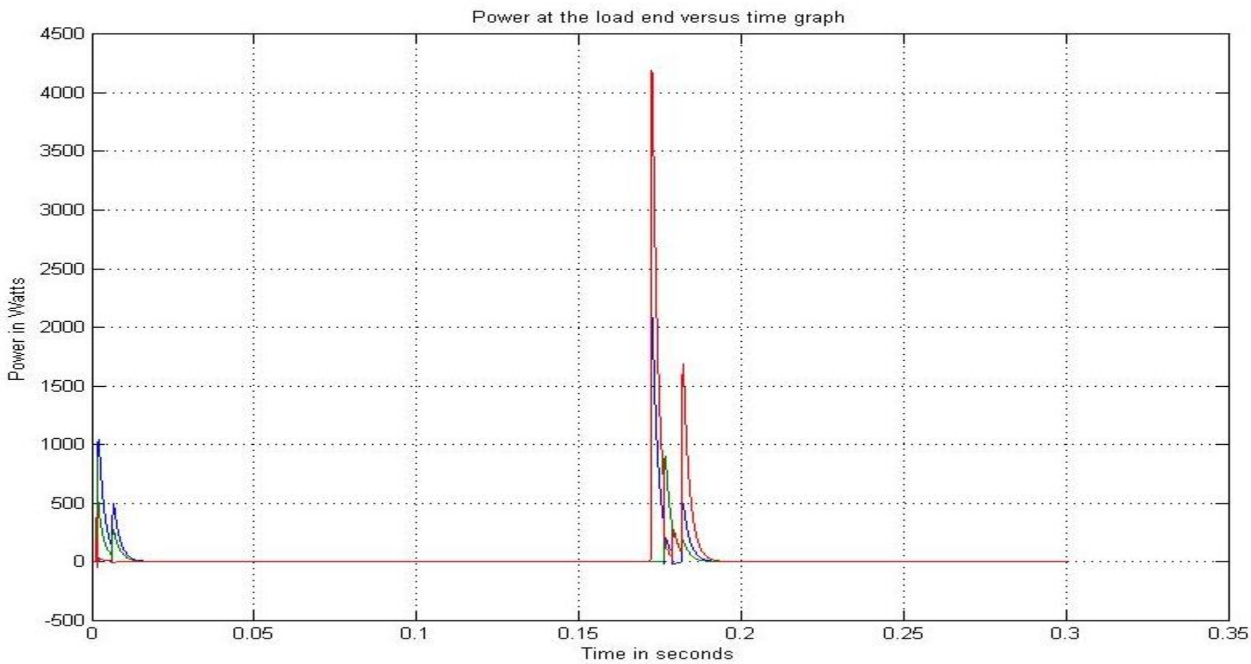

Figure 4.13: Power at the load end

Here, power is found to be maximum at = 4186 Watts at 0.1725 sec.

4.7 CONCLUSION

The MATLAB model consisting of Boost converter with Hybrid Energy Storage Systems (HESS) by using PMSG in RAPS systems is simulated and the observations are recorded and observed. The model is tested at 12mt./sec wind speed. The model is made to run in MATLAB and the observations are recorded and observed. Here, we observe that the power at the load end is found to be maximum at 4186 Watts at 0.1725 sec. So, the maximum power of the Simulink model is found to be 4186 Watts and the maximum power point of the Simulink model is found to be 0.1725 sec.

CHAPTER-5

REGULATING FREQUENCY BY USING PID AND PI CONTROLLER IN A PMSG BASED RAPS NETWORK USING MATLAB

5.1 INTRODUCTION

The RAPS systems are usually small and isolated network of electricity. It becomes necessary for the RAPS system to maintain its stability and reliability of the network for its proper functioning. To accomplish it, it becomes necessary for the system to regulate its frequency. The sudden reversal or disturbance in frequency can occur due to sudden increase or decrease of load or due to improper functioning of system components. So, in order to regulate frequency, we make use of controllers. The controllers are now widely being used in industries as industrial control system. The controllers have played a major role in improving the plant efficiency, process operation and product quality. The controllers have become a major part of the industries in order to regulate its output operations and achieving better efficiency. In order to regulate frequency, we make use of PID and PI controllers. The PID controller is proportional-integral-derivative controller and the PI controller is proportional-integral controller. In PI controller, there is no derivative part. The PID controller is used to calculate the error values. Both PID and PI controllers are widely being used in industrial control systems. Both the controllers are used to give an accurate and optimally controlled output signal.

This chapter suggests to use a PID and PI controller at the load end or the inverter end in a PMSG based RAPS network to enhance the network characteristics. It will finally lead to regulate the frequency of the network. A THD block is used at the scope or workspace end to keep a track of the frequency disturbances in the resultant signals. The lower the THD value, the better is the response characteristics of the network.

5.2 WORKING PRINCIPLE

The research work has to be carried out with the help of some tools like MATLAB software. So, the tool which we will be using in order to carry out our research work will be MATLAB R2013a 64 bit software. The elements like wind turbine block, PMSG (Permanent Magnet Synchronous Generator), rectifier block, inverter block, inductor, capacitor, 3-phase VI measurement block, LC filter block, ultra-capacitor block, battery block, 3-phase transformer, 3-phase RLC load block, etc. required in our work will be taken from “Sim power systems” tool box under “Sim scape” icon present in Simulink library of the MATLAB. We will be utilizing PID and PI controller block present under “Simulink” icon in “Continuous” icon and THD block present in “Sim power systems” (Measurements) tool box under “Sim scape” icon present in Simulink library of the MATLAB. We will be utilizing “Battery” and “Ultra-capacitors” block for hybrid energy storage systems for maintaining the power supply in the network or RAPS systems and improving the stability and reliability of the network. “Powergui” block is used as a generator to the model in order to make it run in MATLAB. We will also be utilizing “Scope” and “Workspace”-block under “Sink” icon present in Simulink library of the MATLAB in order to record the observations or responses after simulating the model. The model is made to run at 50 Hz frequency. First of all, all the blocks are initialized as per requirements and then the model is made to run to check if there are errors present in it or not. Then the Simulink model is made to run or simulate by using MATLAB R2013a 64 bit software tool. The responses are observed by the help of scope or workspace.

The HESS (UCs and Lithium-ion battery), is interfaced into a PMSG based WECS. The PID and PI controllers are used at the inverter end and load end of the network. The THD block is also used at the inverter end and load end of the network. The observations and responses are observed at the inverter end and load end of the network by the help of scope or workspace.

5.3 COMPONENTS

The components present in this work are as follows:-

i. Wind turbine.
ii. Permanent Magnet Synchronous Generator (PMSG).
iii. PID controller.
iv. PI controller.

v. THD block.

i. Wind Turbine:

A wind turbine consists of a turbine which is rotated by means of wind. The wind acts as an input to the wind turbine. The wind turbine is used to generate the mechanical torque, which is then taken as an input to get the electrical energy. The wind turbine has 2 different types of axis-vertical axis and horizontal axis. The smallest of all the wind turbines are used for providing power to traffic warning signs and charging of battery of boats. The larger turbines are used for domestic power supply purposes and have become an important source of renewable energy. Nowadays, many countries have started using wind turbines instead of using fossil fuels. The turbines can rotate in horizontal axis manner or vertical axis manner. The horizontal axis is the older one and the most common one. The wind turbines mostly have a gearbox. The wind turbines are mostly used for production of electric power commercially.

The wind turbine block in MATLAB is a function of wind speeds and pitch angle (beta). It mainly depends on the nature and speed of the wind. It is mostly used in wind farms or in areas where wind is mostly available.

ii. Permanent Magnet Synchronous Generator (PMSG):

PMSG stands for permanent magnet synchronous generator. It is a type of generator where the permanent magnet provides the excitation field. The term synchronous refers to the fact that the rotor and stator rotate with the same speed, and permanent magnet generates the magnetic field and current gets induced into the armature. In commercial purposes, the major source of electrical energy is provided by synchronous generators.

In PMSG, the "rotor" is the permanent magnet, and the "stator" is the armature, which is connected to the load end. Both the stator and the rotor maintain their synchronism with respect to their rotation. The rotor i.e. permanent magnet of the PMSG rotates due to the input given as mechanical torque by the wind turbine. The movement of permanent magnet leads to generate flux which in turn leads to generate the emf and finally leads to generate the voltage at the armature windings. The output voltages of PMSG consists of three phase voltages, which are phase shifted to each other by an angle of 120 degrees. The stator winding of the PMSG carries the three phase armature windings and is electrically displaced by 120 degrees from each other producing an AC voltage output.

In MATLAB, the PMSG is made from Permanent Magnet Synchronous Machine block. Here, the input of Permanent Magnet Synchronous Machine is taken as mechanical torque which makes it as PMSG. The PMSG acts as a generator.

iii. PID Controller:-

A PID Controller is a proportional-integral-derivative controller. It has the ability to use proportional, integral and derivative on the controller output signal to apply and give an accurate and optimal controlled output signal. It is widely used in industrial control systems. The PID controller continuously calculates the error value, i.e., the difference between the set point value and the measured value and then applies the proportional, integral and derivative terms to give the accurate and optimally controlled output signal. Its main objective is to minimize the error value. The calculations regarding PID controller are usually done by the help of Laplace transformation which is usually in s-domain. The proportional, integral and derivative terms are summed up to get the output of the PID Controller. The advantages of the PID controller are fast reaction to disturbances, faster computations and accurate set point temperature control.

iv. PI Controller:-

A PI Controller is a proportional-integral controller. It has the ability to use proportional and integral on the controller output signal to apply and give an accurate and optimal controlled output signal. Here, the derivative part of the controller is not used or the derivative part is set to zero. The calculations regarding PI controller are usually done by the help of Laplace transformation which is usually in s-domain. The proportional and integral terms are summed up to get the output of the PI Controller. The disadvantage of PI controller is slow reaction to disturbances.

v. THD block:-

A THD block is used to calculate the total harmonic distortion (THD) at the output terminals. Here, we have used the THD block at the inverter end and the load end to analyse their responses and calculate their respective THD value.

5.4 PARAMETERS TAKEN

i. Parameters of Wind Turbine:

Table 5.1: Parameters of wind turbine

Sl. No.	Parameter	Value

1.	Nominal mechanical output power (W)	1.5e6
2.	Base power of the electrical generator (VA)	1.5e6/0.9
3.	Base wind speed (m/s)	12
4.	Maximum power at base wind speed (pu of nominal mechanical power)	0.73
5.	Base rotational speed (p.u. of base generator speed)	1.2
6.	Pitch angle beta to display wind-turbine power characteristics (beta >=0) (deg)	0

ii. Parameters of PMSG:

Table 5.2: Parameters of PMSG

Sl. No.	Parameters	Values
1.	Number of phases	3
2.	Back EMF waveform	Sinusoidal
3.	Rotor type	Round
4.	Mechanical input	Torque Tm
5.	Preset model	No
6.	Stator phase resistance Rs (ohm)	0.425
7.	Armature inductance (H)	8.35e-3
8.	Flux linkage established by magnets (V.s)	1.225
9.	Inertia, viscous damping, pole pairs, static friction [J(kg.m^2) F(N.m.s) p() Tf(N.m)]	[2.26e-5 1.35e-5 10 0]
10.	Initial conditions [wm(rad/s) thetam(deg) ia,ib(A)]	[0,0, 12,12]
11.	Sample time	-1

12.	Rotor flux position when theta = 0	90 degrees behind phase A axis (modified park)

iii. Parameters of Diode bridge Rectifier:

Table 5.3: Parameters of Diode bridge Rectifier

Sl. No.	Parameter	Value
1.	Number of bridge arms	3
2.	Snubber resistance Rs (Ohms)	5e-3
3.	Snubber capacitance Cs (F)	1e-6
4.	Power Electronic device	Diodes
5.	Ron (Ohms)	3
6.	Lon (H)	0
7.	Forward voltage Vf (V)	11e3

iv. Parameters of IGBT/ Diode bridge inverter:

Table 5.4: Parameters of IGBT/ Diode bridge inverter

Sl. No.	Parameter	Value
1.	Number of bridge arms	3
2.	Snubber resistance Rs (Ohms)	5
3.	Snubber capacitance Cs (F)	1e-6
4.	Power Electronic device	IGBT/ Diodes
5.	Ron (Ohms)	3

6.	Forward voltages [Device Vf(V) , Diode Vfd(V)]	[11e3 0.7]
7.	[Tf (s) , Tt (s)]	[1e-6 2e-6]

v. Parameters of Ultra-Capacitors (UCs):

Table 5.5: Parameters of Ultra-Capacitors (UCs)

Sl. No.	**Parameter**	**Value**
1.	Resistance R (Ohms)	2e-3
2.	Capacitance C (F)	150

vi. Parameters of Batteries:

Table 5.6: Parameters of Batteries

Sl. No.	**Parameter**	**Value**
1.	Battery type	Lithium-Ion
2.	Nominal Voltage (V)	1.2
3.	Rated Capacity (Ah)	1.5
4.	Initial State-Of-Charge (%)	50
5.	Discharge current [i1, i2, i3,...] (amps)	[1.5 3]
6.	Units	Ampere-hour
7.	Battery response time (s)	30

vii. Parameters of LC filter:

Table 5.7: Parameters of LC filter

Sl. No.	Parameters	Values
1.	Branch Type	LC
2.	Inductance L (H)	2e-3
3.	Capacitance C (F)	1e-6

viii. Parameters of Three phase transformer (Star-Delta):

Table 5.8: Parameters of Three phase transformer (Star-Delta)

Sl. No.	Parameter	Values
1.	Winding 1 connection (ABC terminals)	Yg
2.	Winding 2 connection (abc terminals)	Delta (D11)
3.	Units	SI
4.	Nominal power and frequency [Pn(VA) , fn(Hz)]	[100e3 , 50]
5.	Winding 1 parameters [V1 Ph-Ph(Vrms) , R1(ohm) , L1(H)]	[11000 2.42 0.30812]
6.	Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(ohm) , L2(H)]	[400 0.0096 0.0012223]
7.	Magnetization resistance Rm (ohm)	6.05e+05
8.	Magnetization inductance Lm (H)	1925.8

ix. Parameters of Three phase Parallel RLC load of RAPS system:

Table 5.9: Parameters of Three phase Parallel RLC load of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	100
7.	Load type	Constant Z

x. Parameters of Three phase Parallel RLC load1 of RAPS system:

Table 5.10: Parameters of Three phase Parallel RLC load1 of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	70
7.	Load type	Constant Z

xi. Parameters of Three phase Parallel RLC load2 of RAPS system:

Table 5.11: Parameters of Three phase Parallel RLC load2 of RAPS system

Sl. No.	Parameter	Value
1.	Configuration	Y (grounded)
2.	Nominal phase-to-phase voltage Vn (Vrms)	400
3.	Nominal frequency fn (Hz)	50
4.	Active power P (W)	10e3
5.	Inductive reactive Power QL (positive var)	100
6.	Capacitive reactive power Qc (negative var)	50
7.	Load type	Constant Z

xii. Parameters of Three phase V-I measurement2 block:

Table 5.12: Parameters of Three phase V-I measurement2 block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xiii. Parameters of Three phase V-I measurement block:

Table 5.13: Parameters of Three phase V-I measurement block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xiv. Parameters of Three phase V-I measurement1 block:

Table 5.14: Parameters of Three phase V-I measurement1 block

Sl. No.	Parameter	Value
1.	Voltage measurement	Phase-to-phase
2.	Current measurement	Yes

xv. Parameters of SVPWM generator (2-level) block:

Table 5.15: Parameters of SVPWM generator (2-level) block

Sl. No.	Parameter	Value
1.	Data type of input reference vector (Uref)	Internally generated
2.	Switching pattern	Pattern #1
3.	PWM frequency (Hz)	50
4.	Output voltage: [Mag (0<m<1), Phase (degrees), Freq (Hz)]	[0.8 0 50]
5.	Sample time	1e-6

xvi. Parameters of Capacitor:

Table 5.16: Parameters of Capacitor

Sl. No.	Parameter	Value
1.	Branch type	C
2.	Capacitance C (F)	1e-6
3.	Measurements	Branch voltage and current

xvii. Parameters of Capacitor1:

Table 5.17: Parameters of Capacitor1

Sl. No.	Parameter	Value
1.	Branch type	C
2.	Capacitance C (F)	1e-6
3.	Measurements	Branch voltage and current

xviii. **Parameters of Inductor:**

Table 5.18: Parameters of Inductor

Sl. No.	Parameter	Value
1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xix. **Parameters of Inductor1:**

Table 5.19: Parameters of Inductor1

Sl. No.	Parameter	Value
1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xx. **Parameters of Inductor2:**

Table 5.20: Parameters of Inductor2

Sl. No.	Parameter	Value

1.	Branch type	L
2.	Inductance L (H)	1e-3
3.	Measurements	Branch voltage and current

xxi. Parameters of PID Controller:

Table 5.21: Parameters of PID Controller

Sl. No.	Parameter	Value
1.	Controller	PID
2.	Form	Parallel
3.	Time domain	Continuous-time
4.	Proportional (P)	1
5.	Integral (I)	1
6.	Derivative (D)	1
7.	Filter coefficient (N)	100
8.	Source	internal

xxii. Parameters of THD:

Table 5.22: Parameters of THD

Sl. No.	Parameter	Value
1.	Fundamental frequency of input signal (Hz)	50
2.	Sample time	0

xxiii. Parameters of PI Controller:

Table 5.23: Parameters of PI Controller

Sl. No.	Parameter	Value
1.	Controller	PI
2.	Form	Parallel
3.	Time domain	Continuous-time
4.	Proportional (P)	1
5.	Integral (I)	1
6.	Source	internal
7.	Integrator	0

5.5 SIMULINK MODEL

The Simulink model is made in MATLAB R2013a, 64 bit software and is checked for errors if present. The Simulink model is made to run or simulate in MATLAB.

5.5.1 Simulink model using PID Controller:-

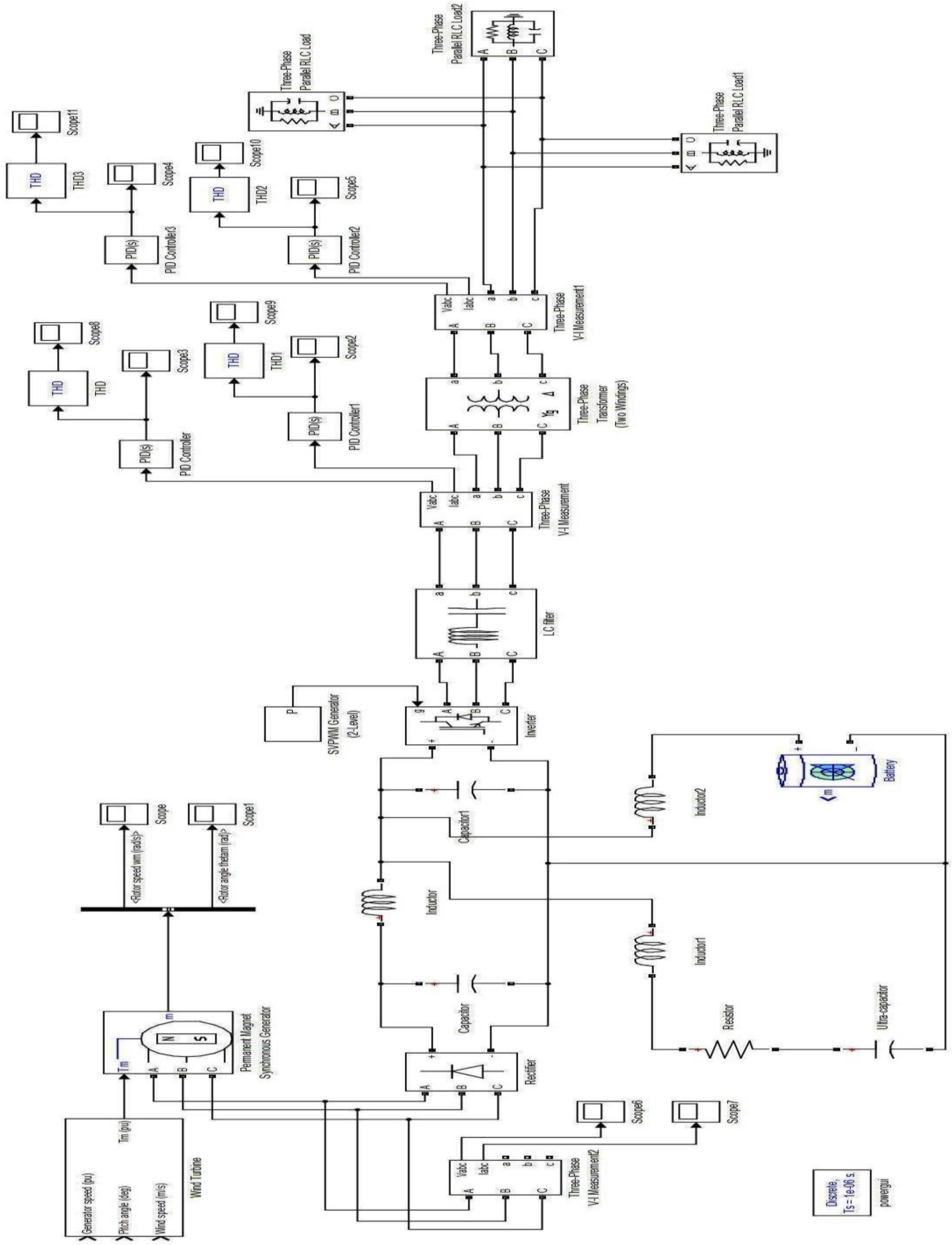

Figure 5.1: Simulink model using PID Controller

5.5.2 Simulink model using PI Controller:-

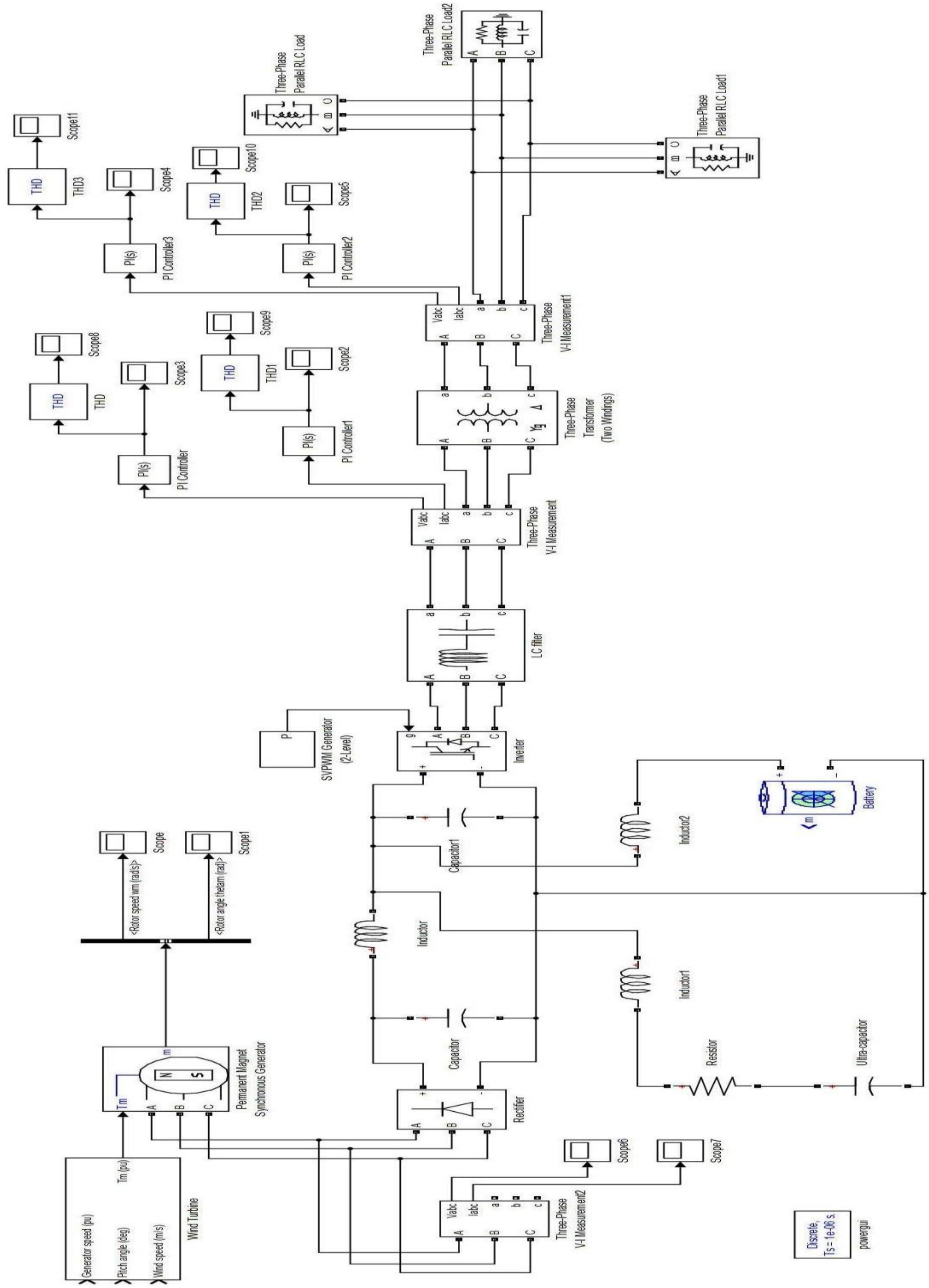

Figure 5.2: Simulink model using PI Controller

5.6 RESULTS

The Simulation or MATLAB model is made to run in MATLAB and the responses are recorded and observed.

5.6.1 Results of model using PID Controller:-

a. Output Voltage of PMSG:-

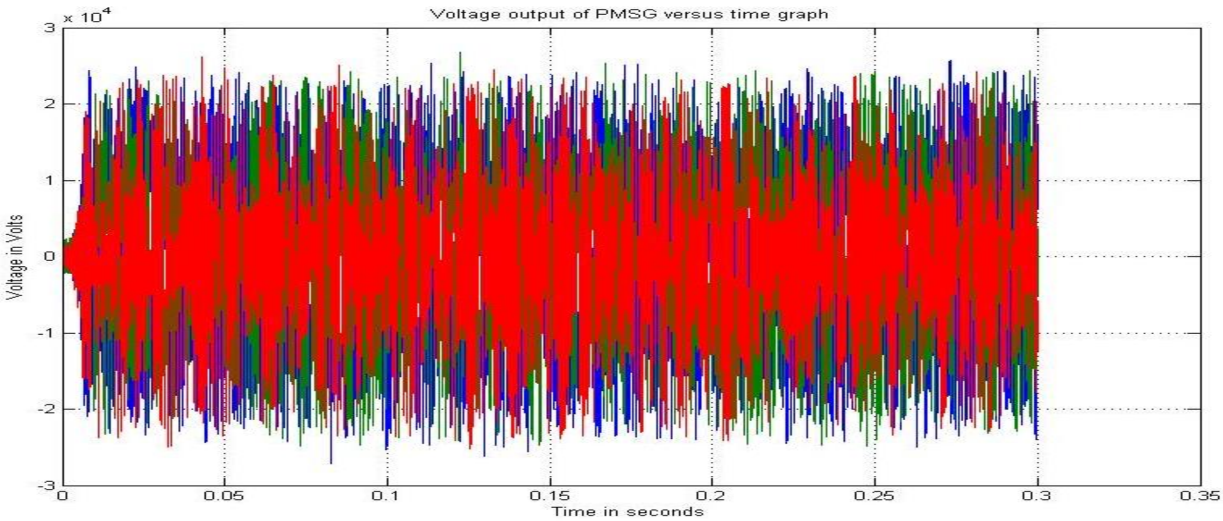

Figure 5.3: Output Voltage of PMSG

The phase voltage output of the PMSG is found to be = 25383 Volts = 25.383 KV.

b. Voltage output at the inverter end:- Voltage = 1.1*10^6 Volts

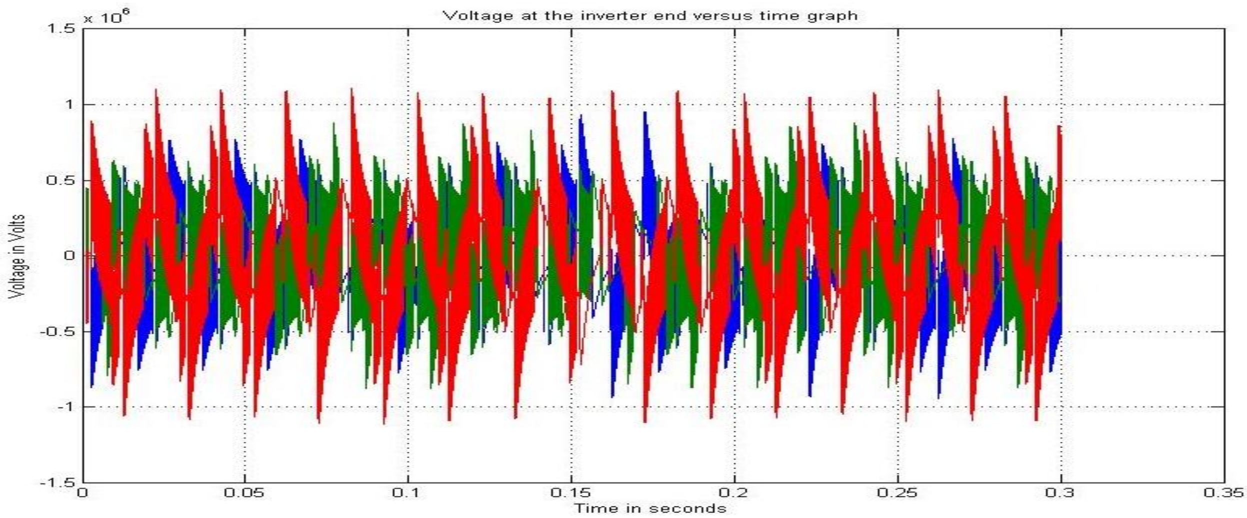

Figure 5.4: Voltage output at the inverter end

The voltage output at the inverter end is found to be = 1.1 *10^6 Volts.

c. **Current output at the inverter end:-** Current = 102 A

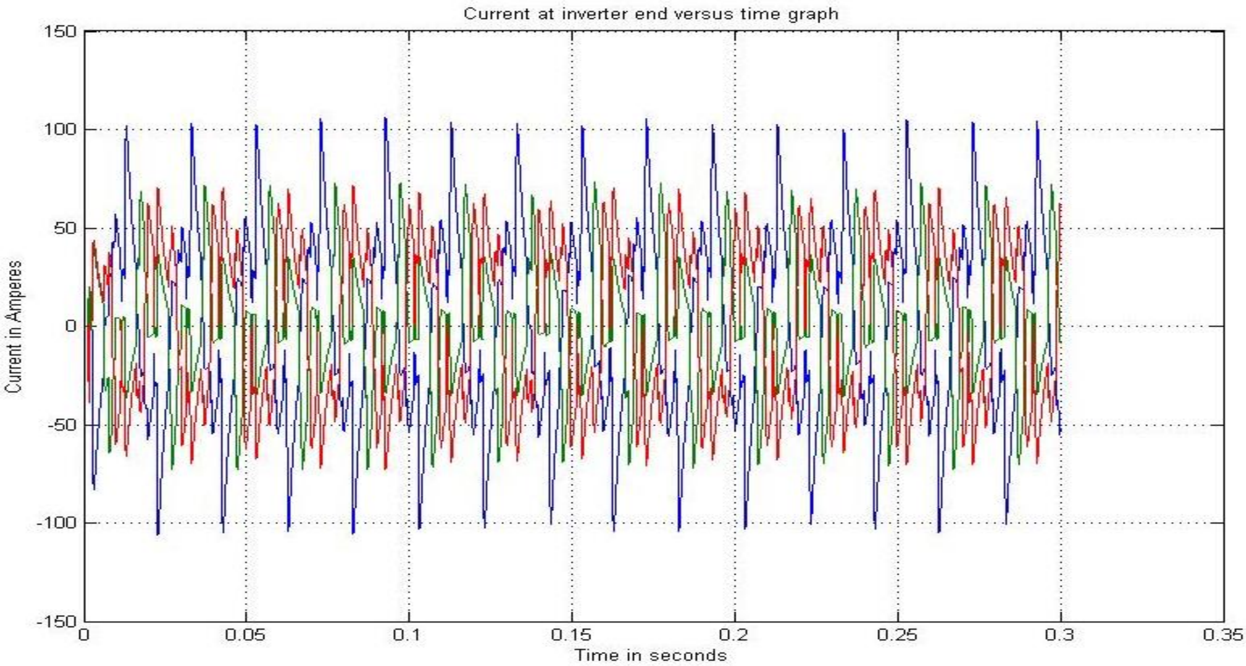

Figure 5.5: Current output at the inverter end

The current output at the inverter end is found to be = 102 A.

d. **THD of Voltage at the inverter end:-** THD = 2.5886

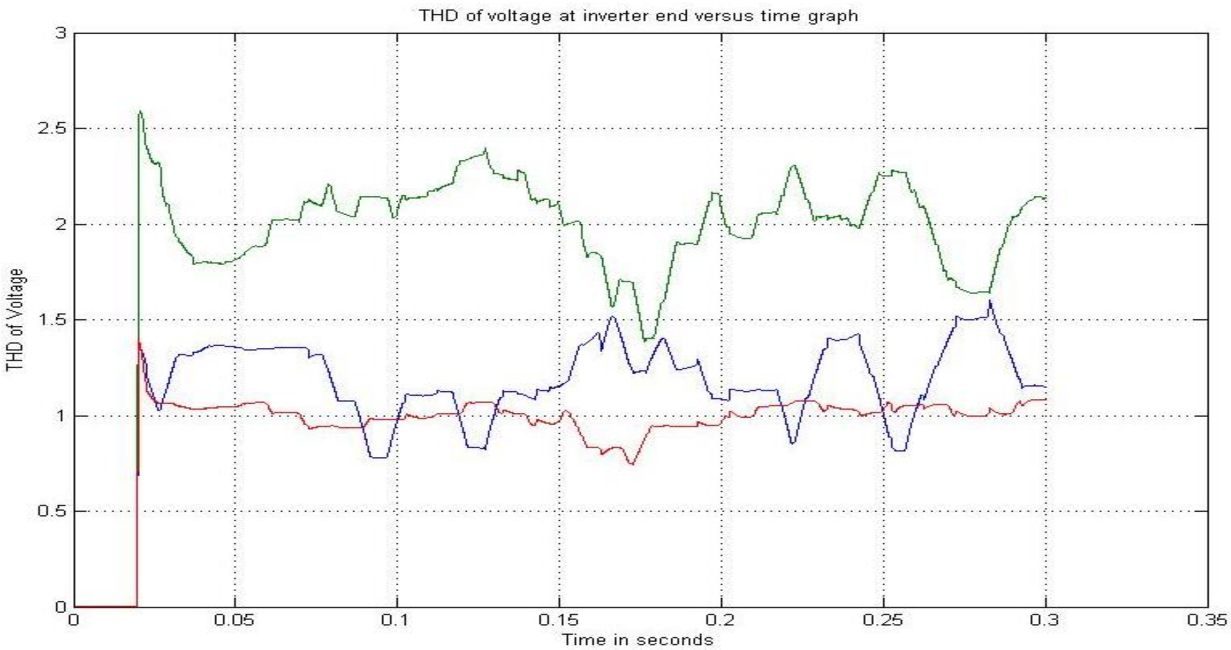

Figure 5.6: THD of Voltage at the inverter end

The THD of voltage at the inverter end is found to be = 2.5886.

e. THD of Current at the inverter end:- THD = 1.8505

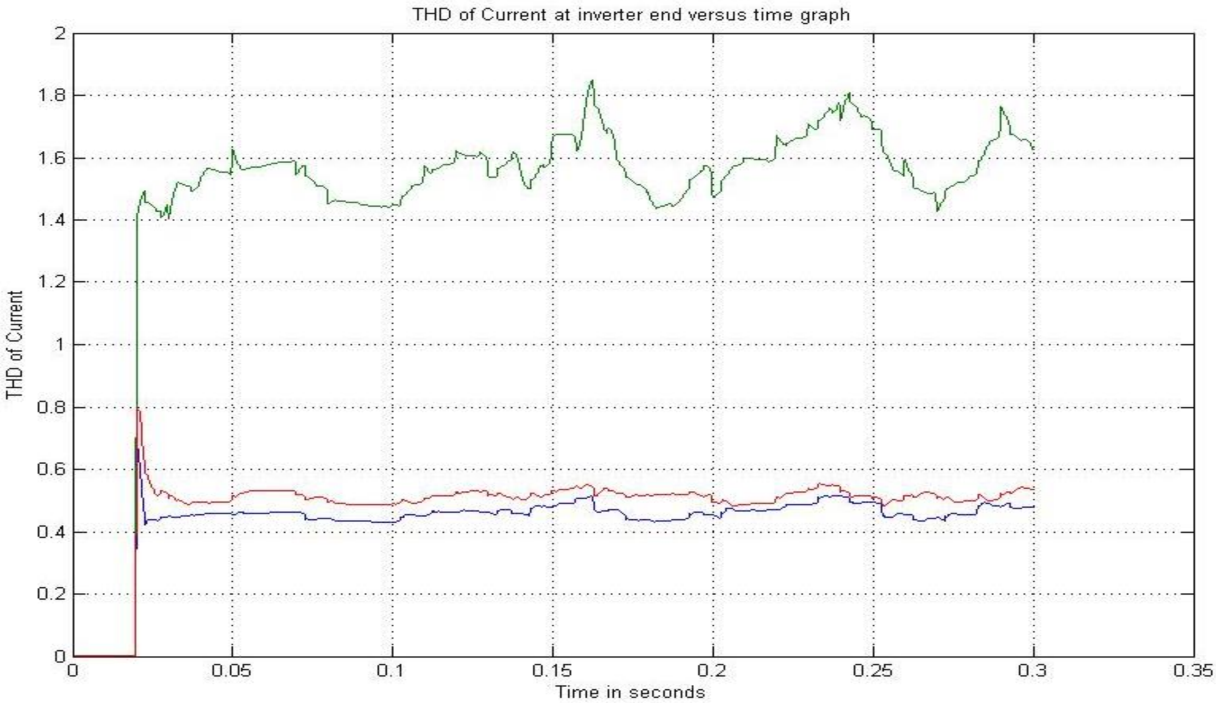

Figure 5.7: THD of Current at the inverter end

The THD of current at the inverter end is found to be = 1.8505.

f. Voltage at the load end:- Voltage = $2.67*10^4$ Volts

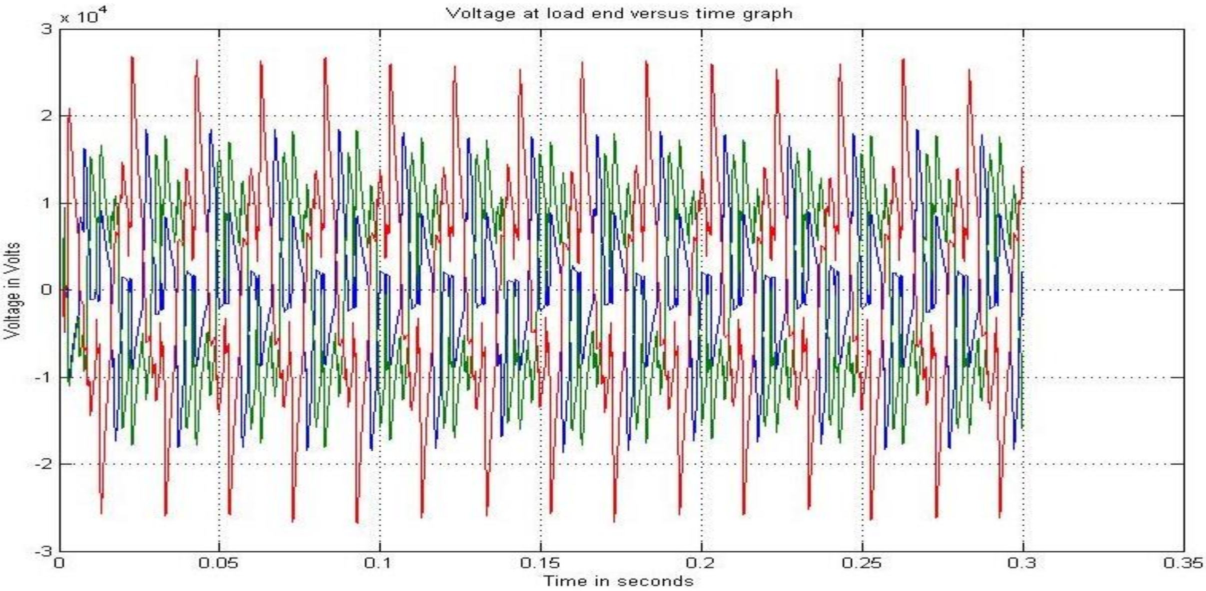

Figure 5.8: Voltage at the load end

The voltage at the load end is found to be = $2.67 * 10^4$ Volts.

g. Current at the load end:- Current = 2783 A

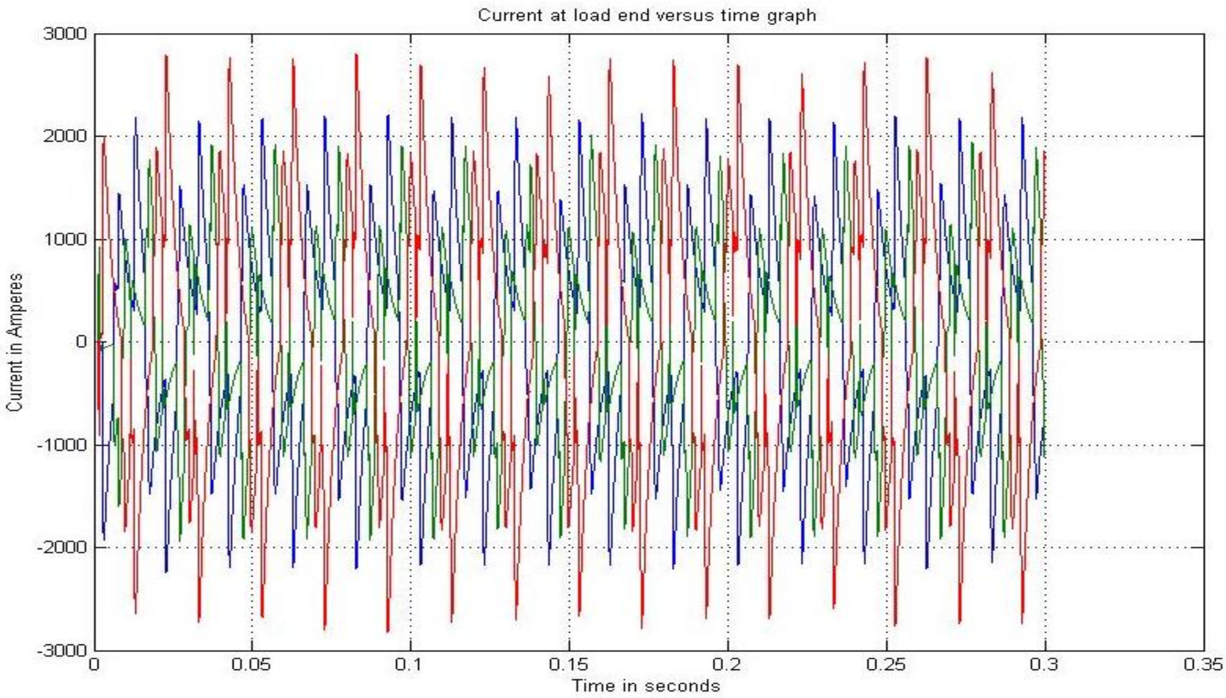

Figure 5.9: Current at the load end

The current at the load end is found to be = 2783 A.

h. THD of Voltage at the load end:- THD = 1.85

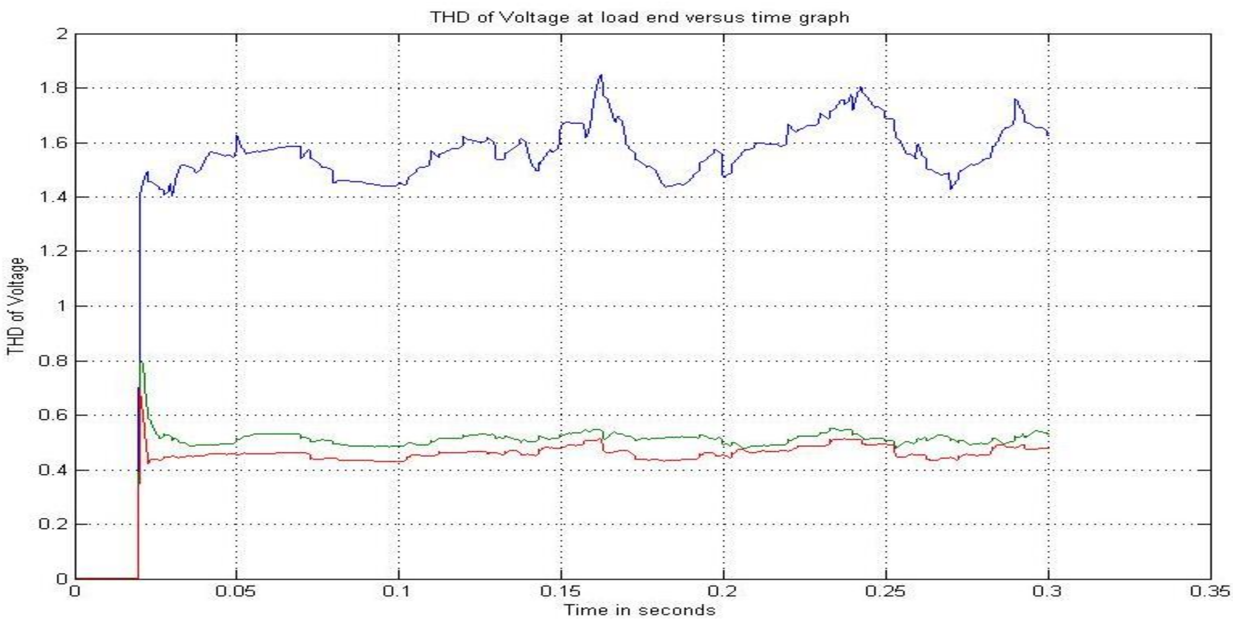

Figure 5.10: THD of Voltage at the load end

The THD of voltage at the load end is found to be = 1.85.

i. **THD of Current at the load end:-** THD = 1.5087

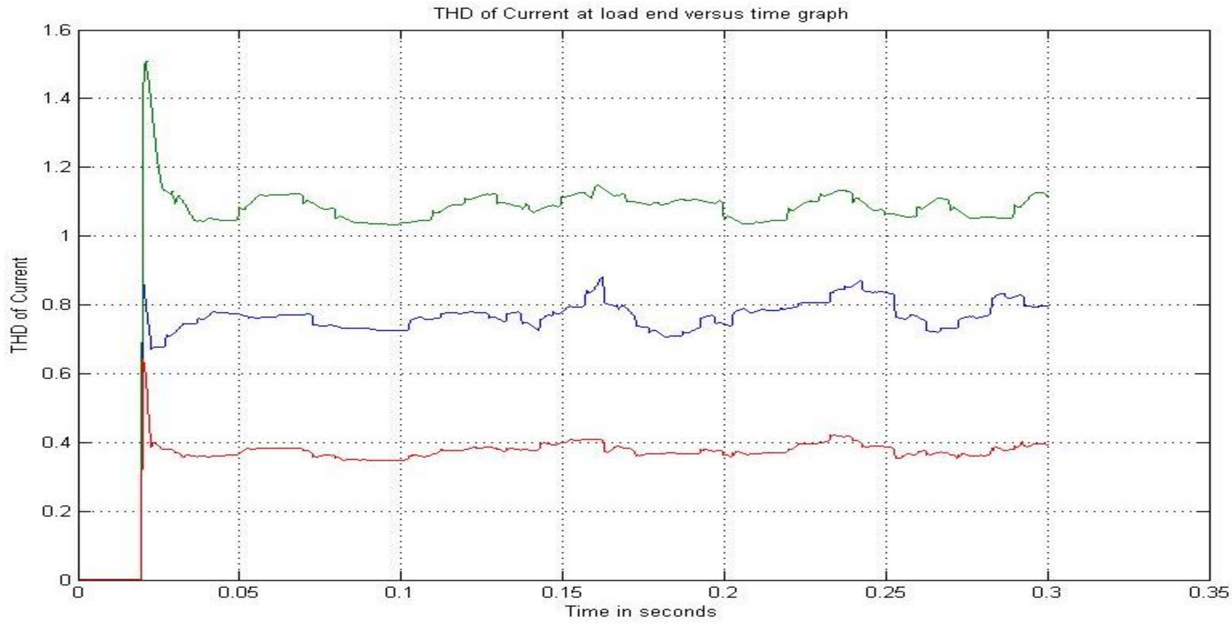

Figure 5.11: THD of Current at the load end

The THD of current at the load end is found to be = 1.5087.

j. **Voltage at load end at 10 m/sec wind speed:-** Voltage = $2.68*10^4$ Volts

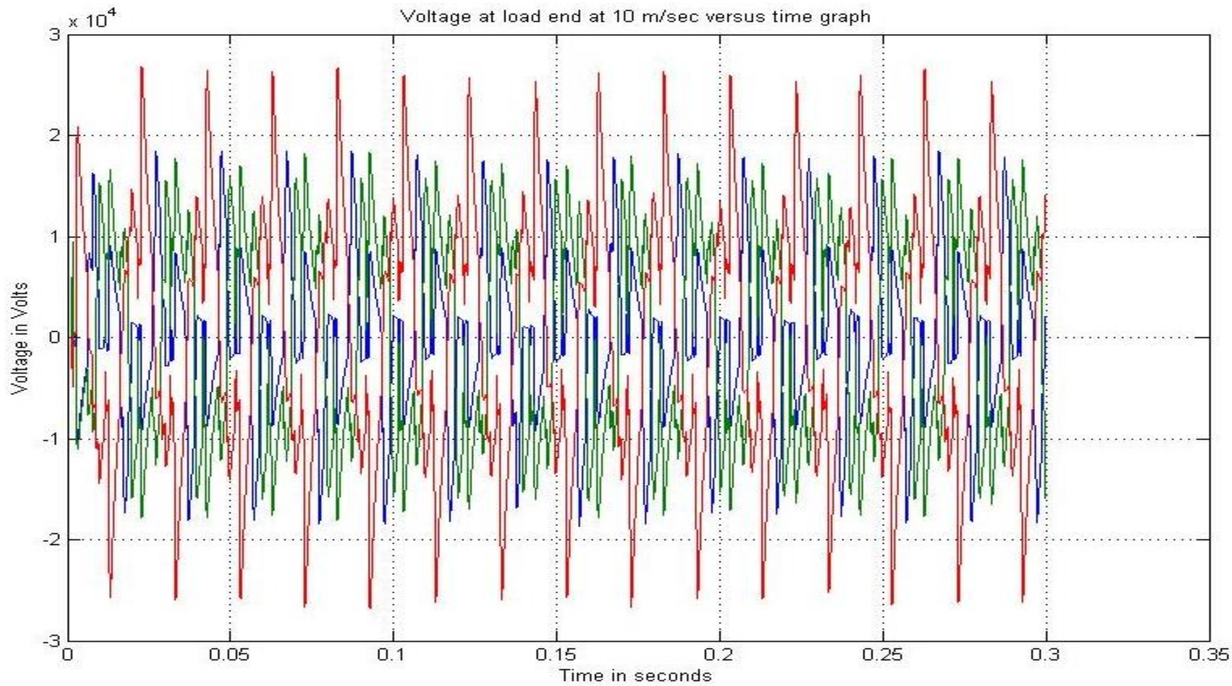

Figure 5.12: Voltage at load end at 10 m/sec wind speed

The voltage at the load end at 10 m/sec wind speed is found to be = $2.68*10^4$ Volts.

k. **Current at load end at 10 m/sec wind speed:-** Current = 2783 A

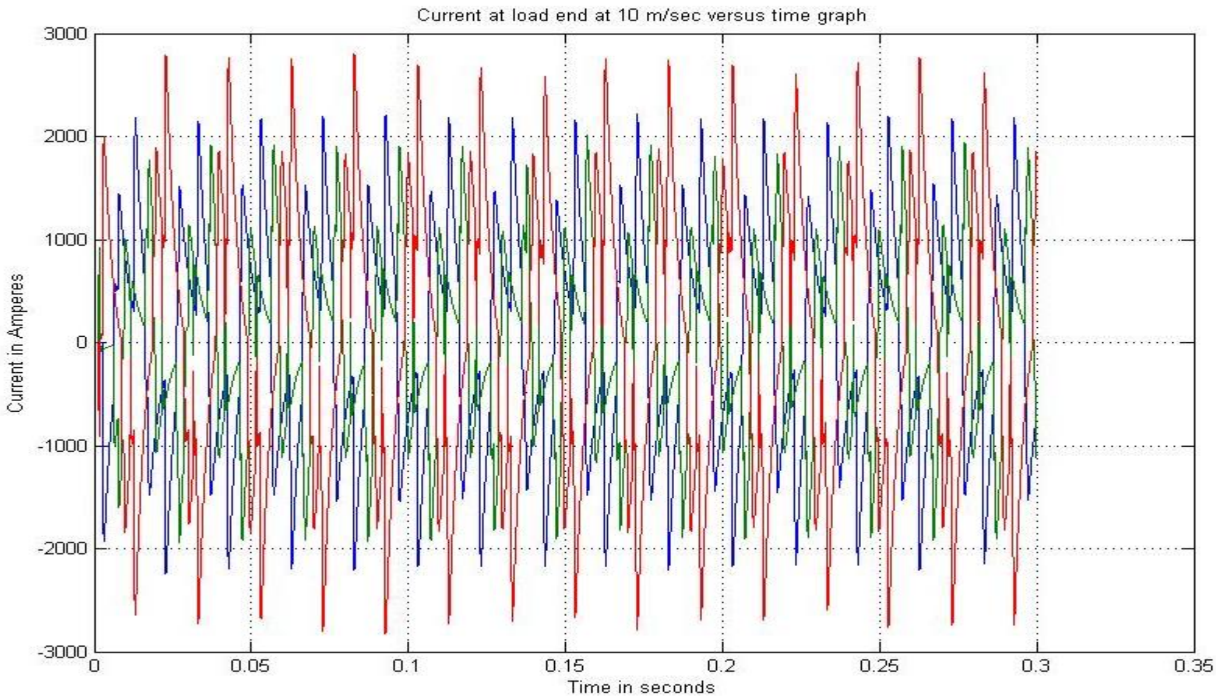

Figure 5.13: Current at load end at 10 m/sec wind speed

The current at the load end at 10 m/sec wind speed is found to be = 2783 A.

l. **Voltage at load end at 8 m/sec wind speed:-** Voltage = $2.68*10^4$ Volts

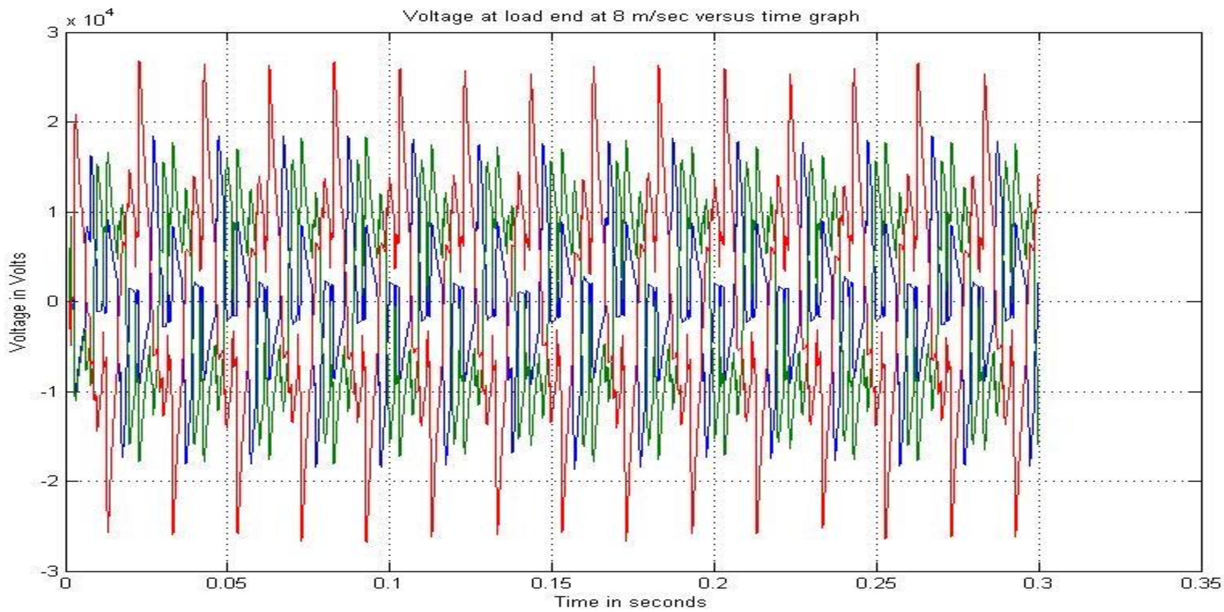

Figure 5.14: Voltage at load end at 8 m/sec wind speed

The voltage at the load end at 8 m/sec wind speed is found to be = $2.68*10^4$ Volts.

m. Current at load end at 8 m/sec wind speed:- Current = 2783 A

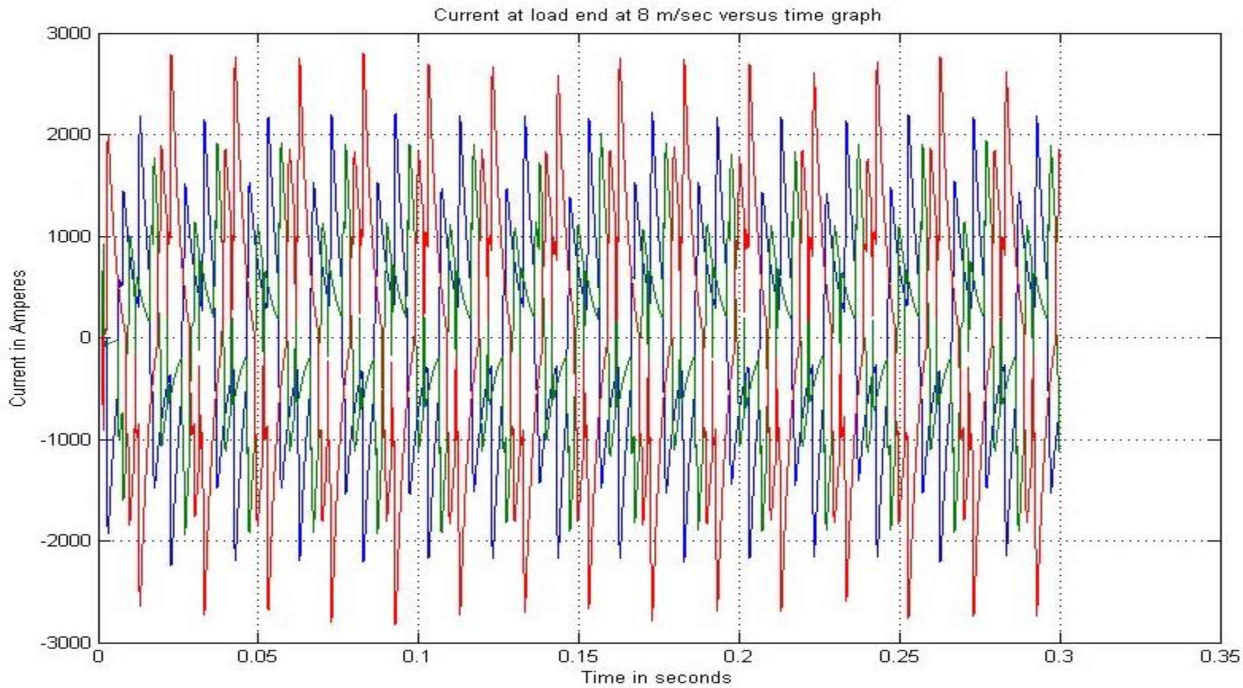

Figure 5.15: Current at load end at 8 m/sec wind speed

The current at the load end at 8 m/sec wind speed is found to be = 2783 A.

n. Voltage at load end at 5 m/sec wind speed:- Voltage = $2.68*10^4$ Volts

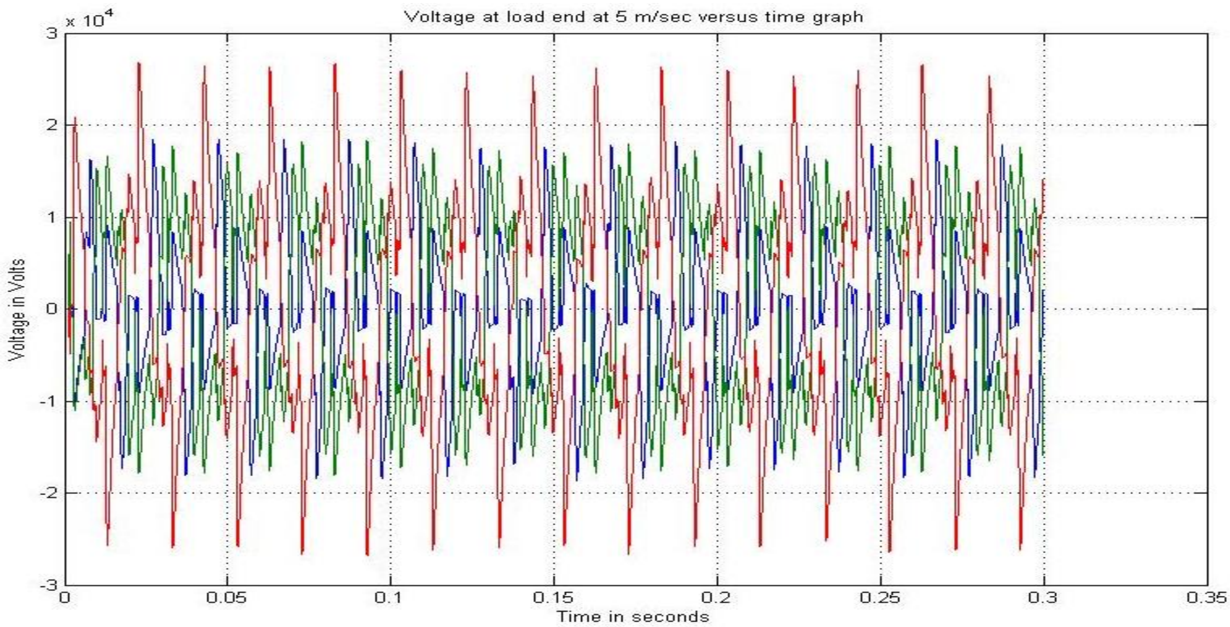

Figure 5.16: Voltage at load end at 5 m/sec wind speed

The voltage at the load end at 5 m/sec wind speed is found to be = $2.68*10^4$ Volts.

o. Current at load end at 5 m/sec wind speed:- Current = 2783 A

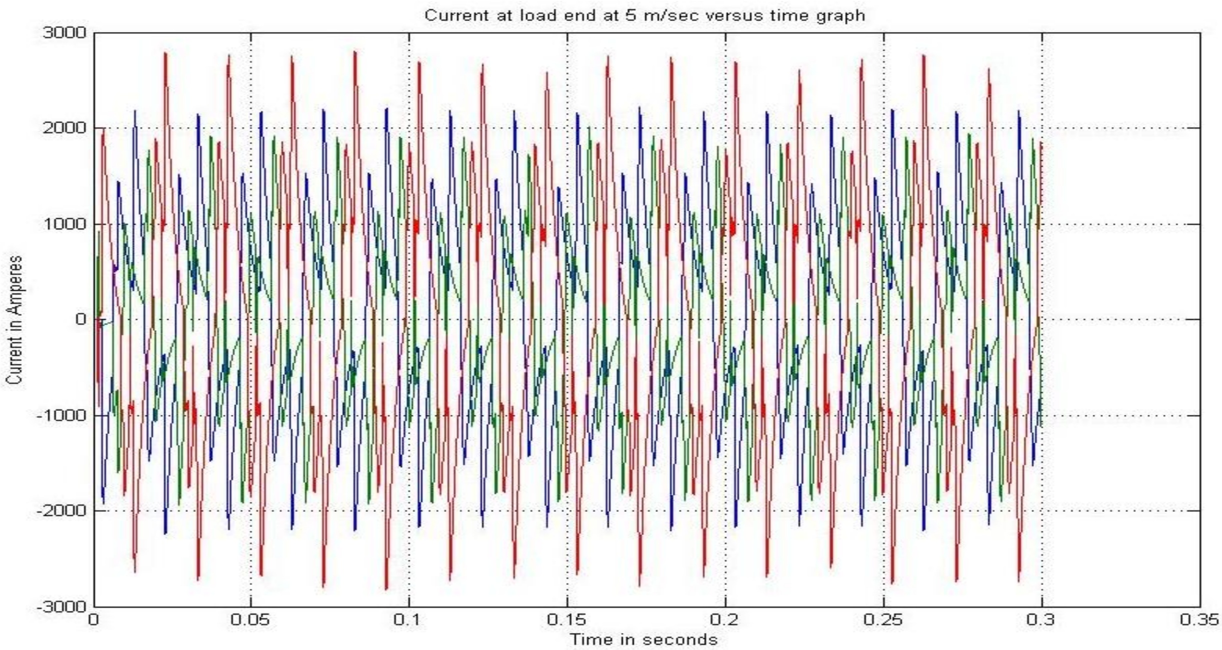

Figure 5.17: Current at load end at 5 m/sec wind speed

The current at the load end at 5 m/sec wind speed is found to be = 2783 A.

5.6.2 Results of model using PI Controller:-

a. Output Voltage of PMSG:-

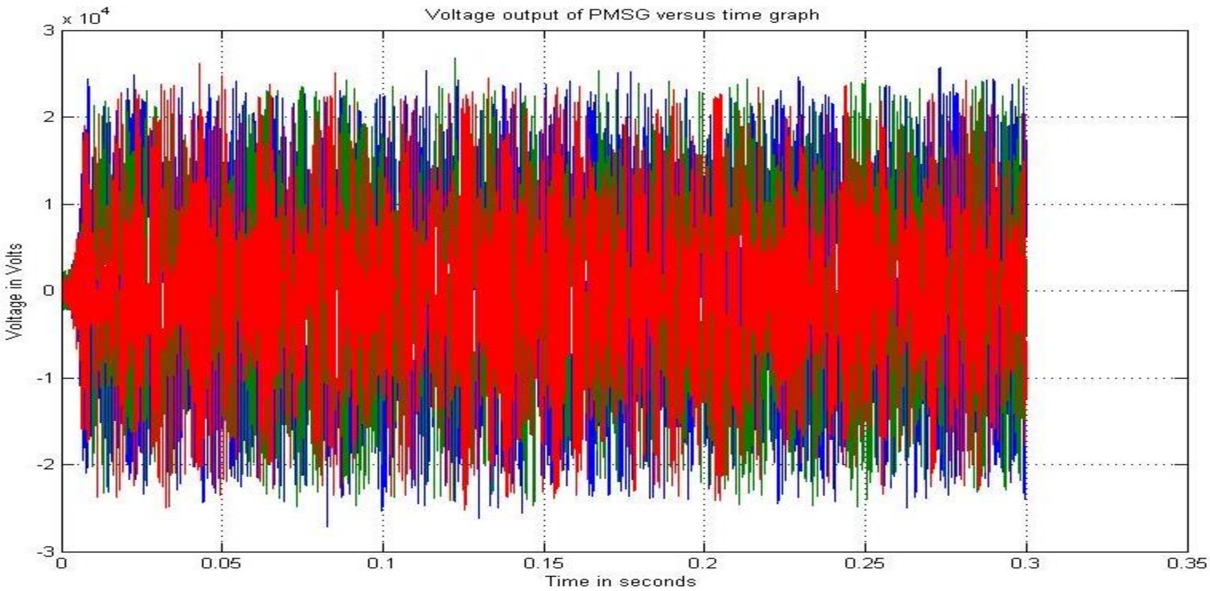

Figure 5.18: Output Voltage of PMSG

The phase voltage output of the PMSG is found to be = 25383 Volts = 25.383 KV.

b. **Voltage output at the inverter end:-** Voltage = $1.059*10^4$ Volts

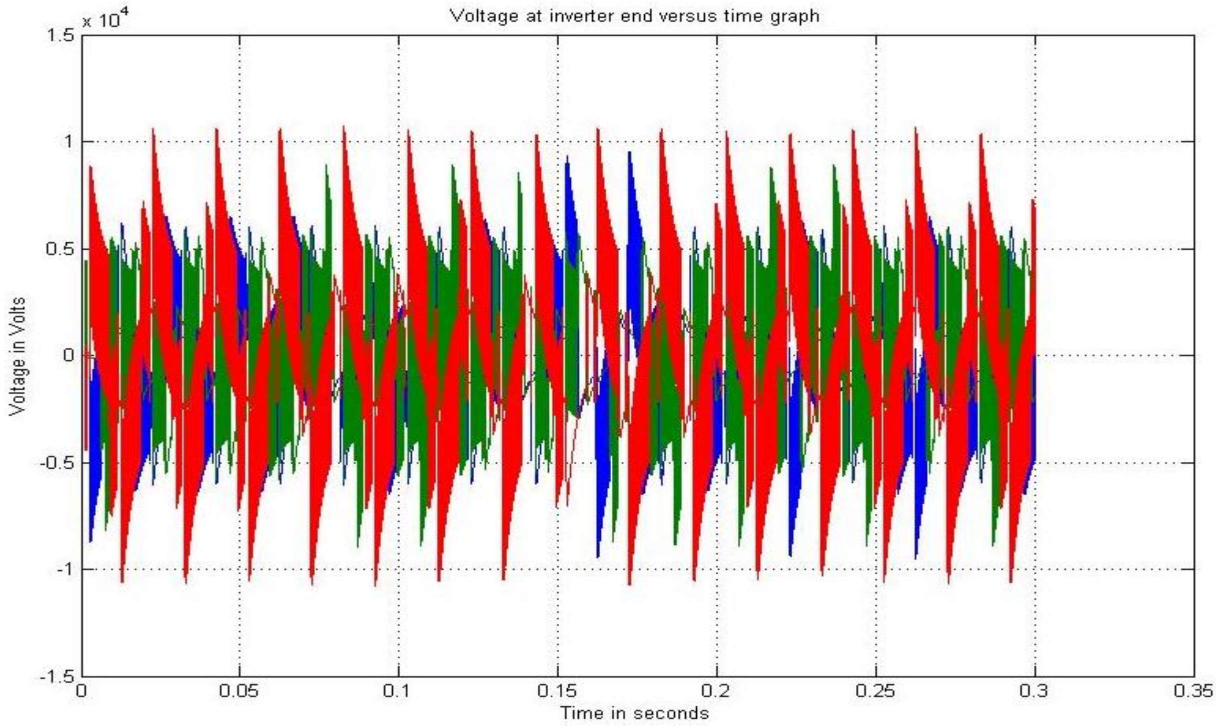

Figure 5.19: Voltage output at the inverter end

The voltage output at the inverter end is found to be = $1.059*10^4$ Volts.

c. **Current output at the inverter end:-** Current = 1.05 A

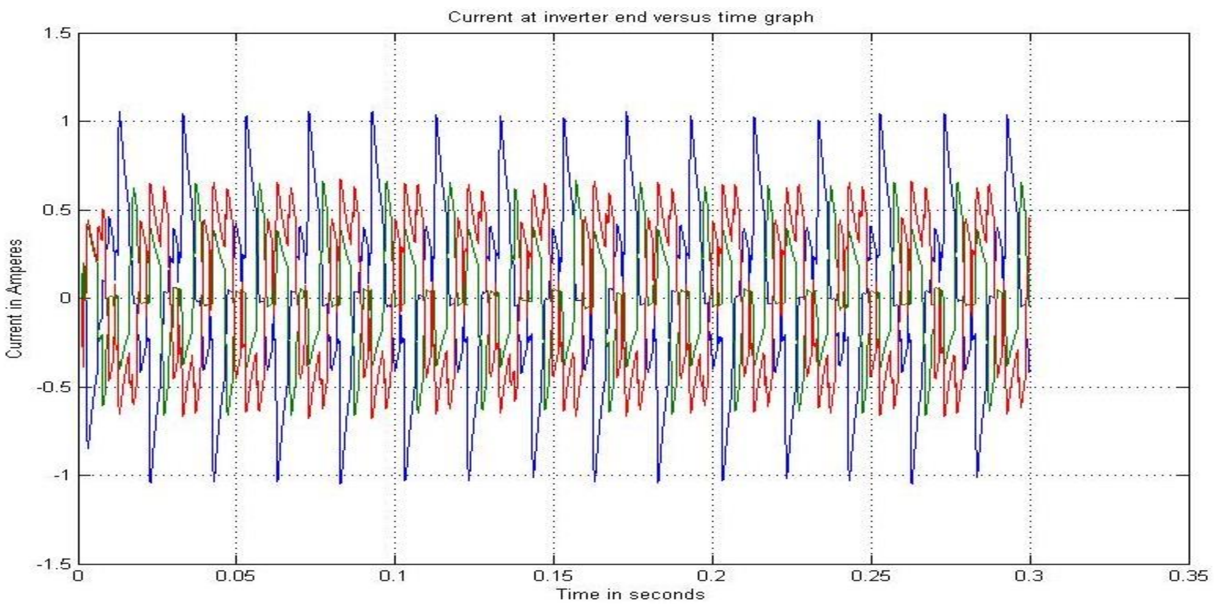

Figure 5.20: Current output at the inverter end

The current output at the inverter end is found to be = 1.05 A.

d. THD of Voltage at the inverter end:- THD = 2.22

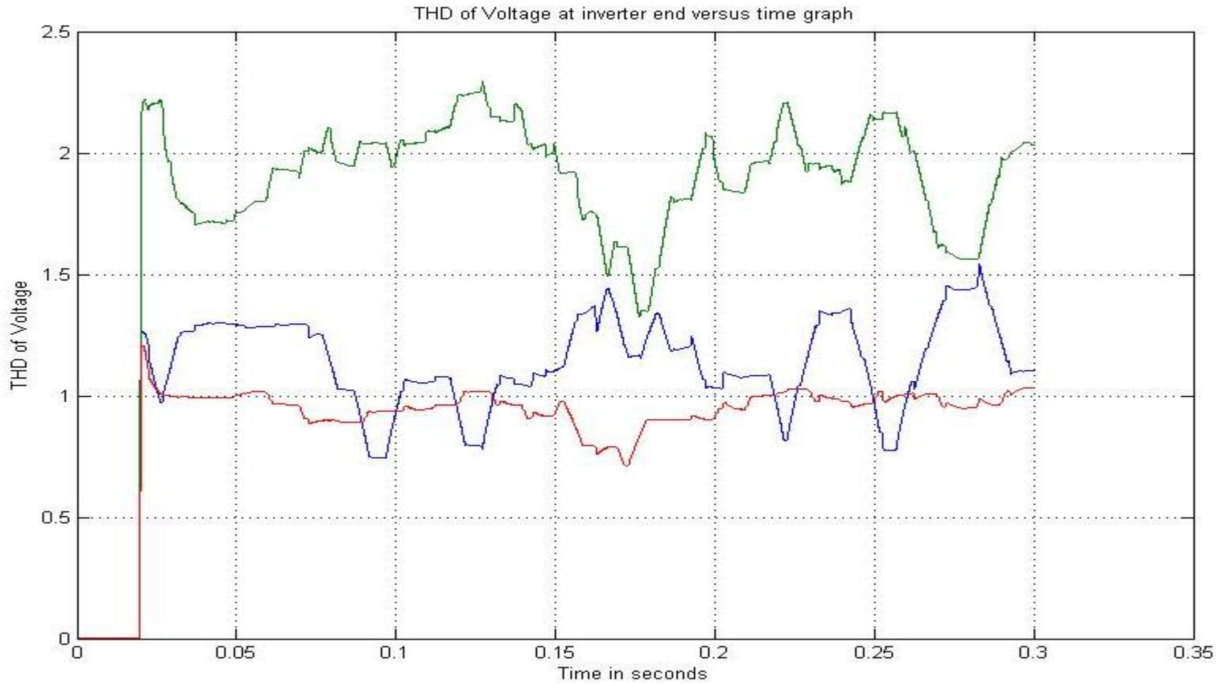

Figure 5.21: THD of Voltage at the inverter end

The THD of voltage at the inverter end is found to be = 2.22.

e. THD of Current at the inverter end:- THD = 1.7616

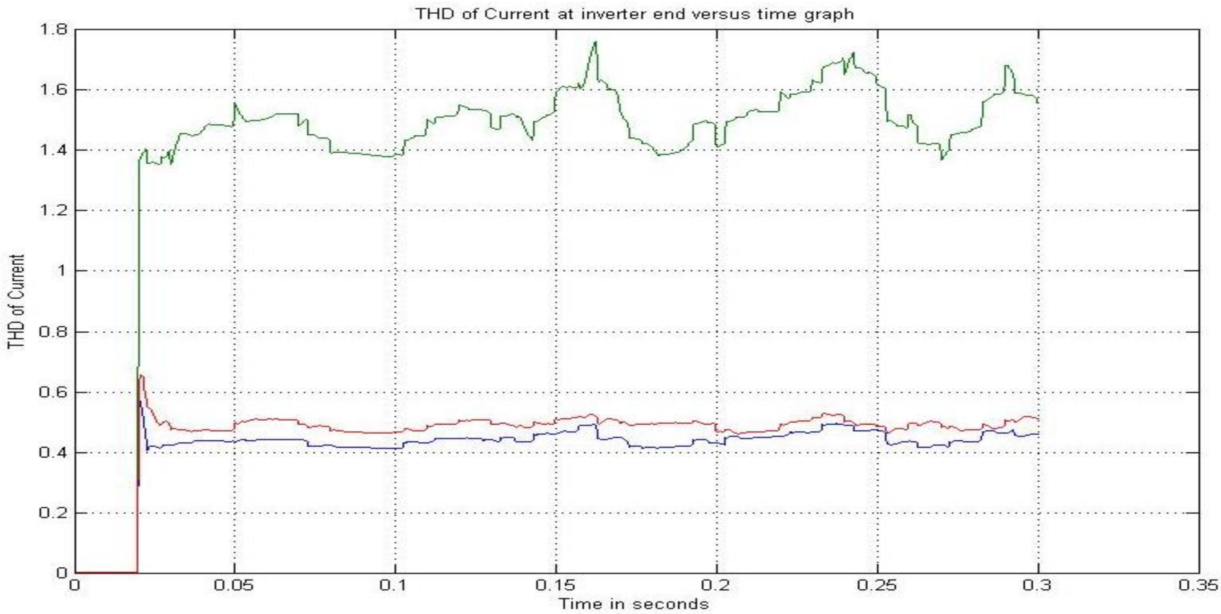

Figure 5.22: THD of Current at the inverter end

The THD of current at the inverter end is found to be = 1.7616.

f. **Voltage at the load end:-** Voltage = 263.5 Volts

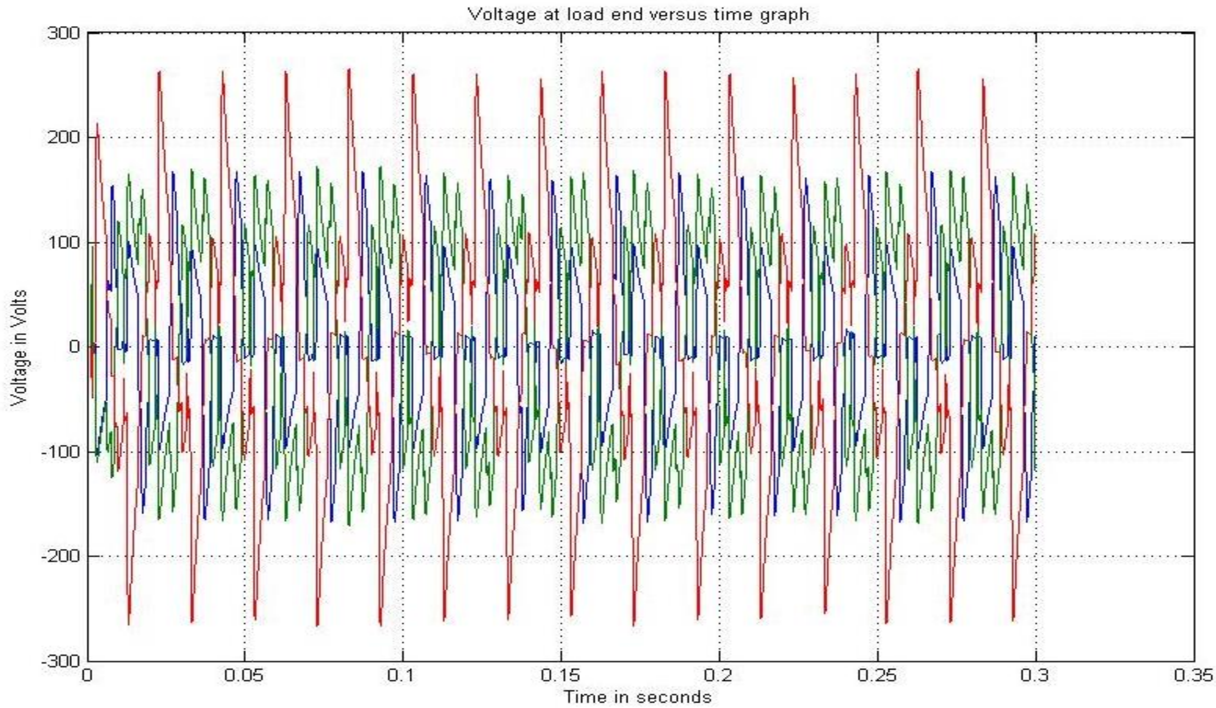

Figure 5.23: Voltage at the load end

The voltage at the load end is found to be = 263.5 Volts.

g. **Current at the load end:-** Current = 26.74 A

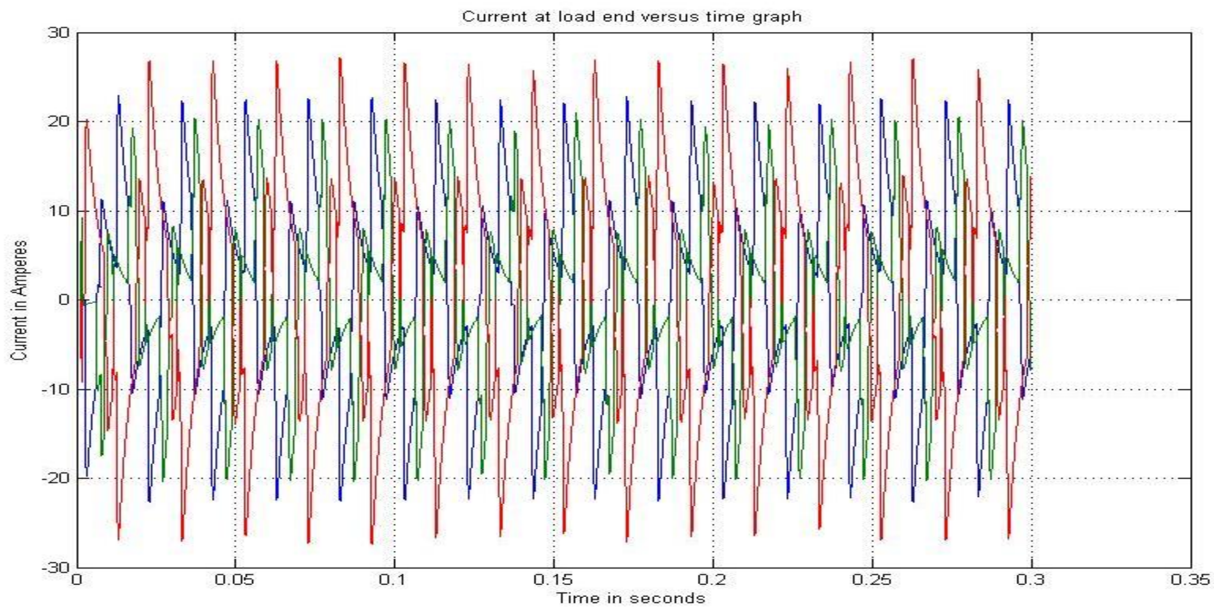

Figure 5.24: Current at the load end

The current at the load end is found to be = 26.74 A.

h. THD of Voltage at the load end:- THD = 1.7611

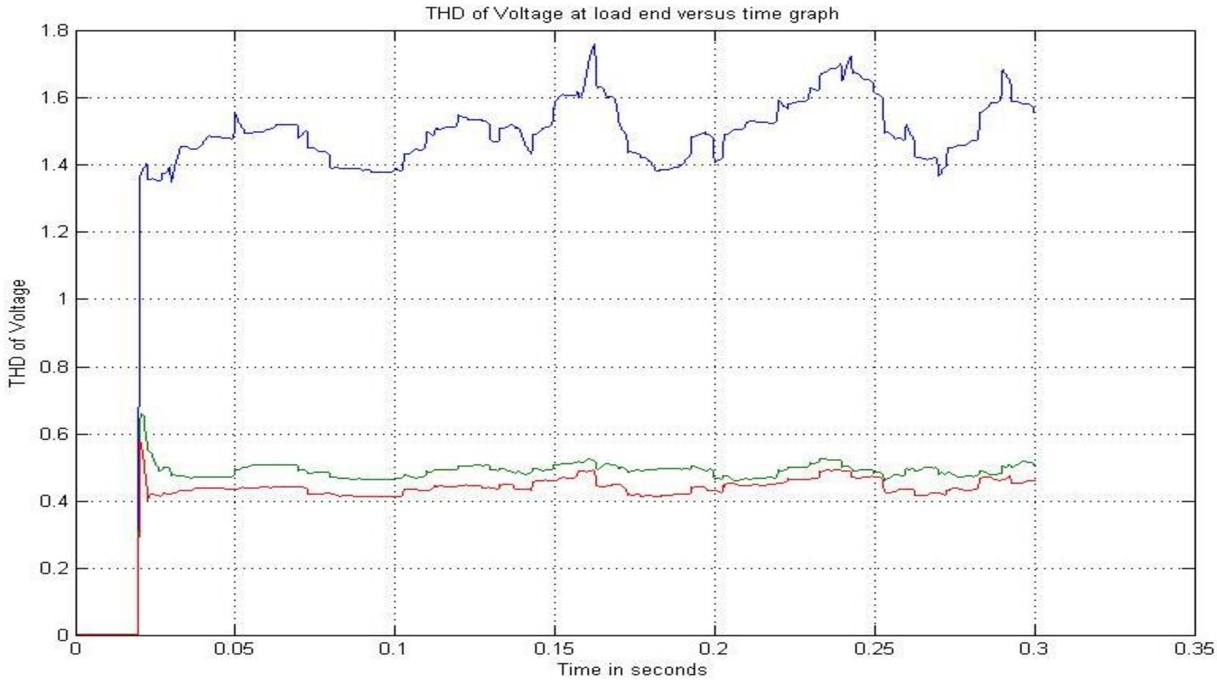

Figure 5.25: THD of Voltage at the load end

The THD of voltage at the load end is found to be = 1.7611.

i. THD of Current at the load end:- THD = 1.2905

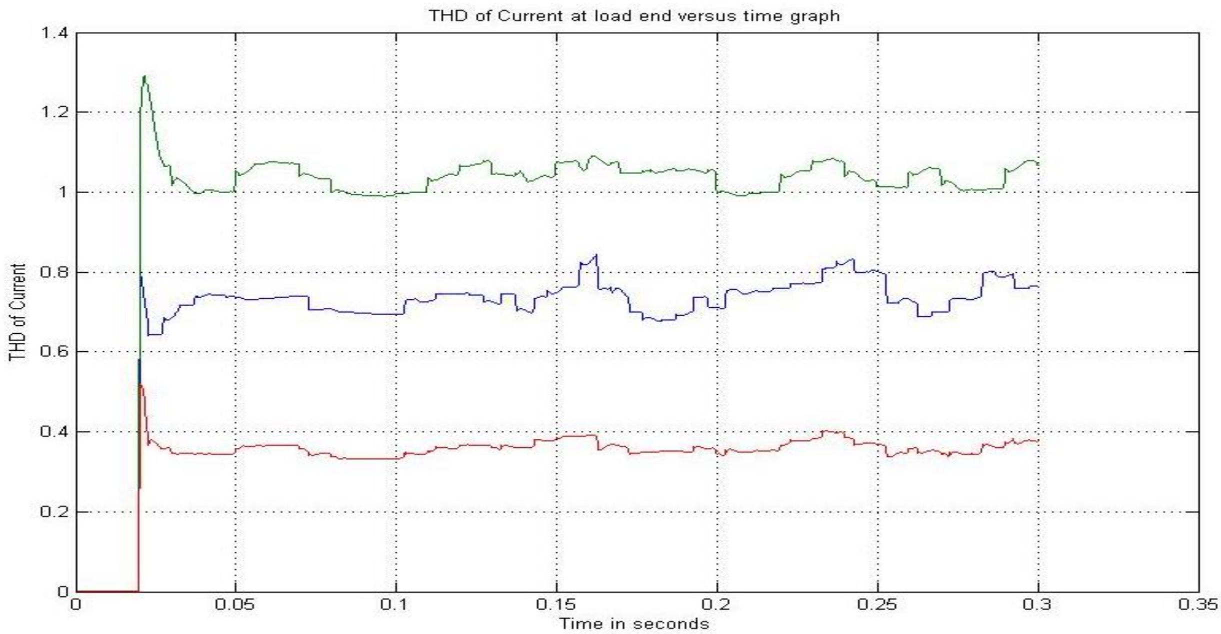

Figure 5.26: THD of Current at the load end

The THD of current at the load end is found to be = 1.2905.

j. Voltage at load end at 10 m/sec wind speed:- Voltage = 263.5 Volts

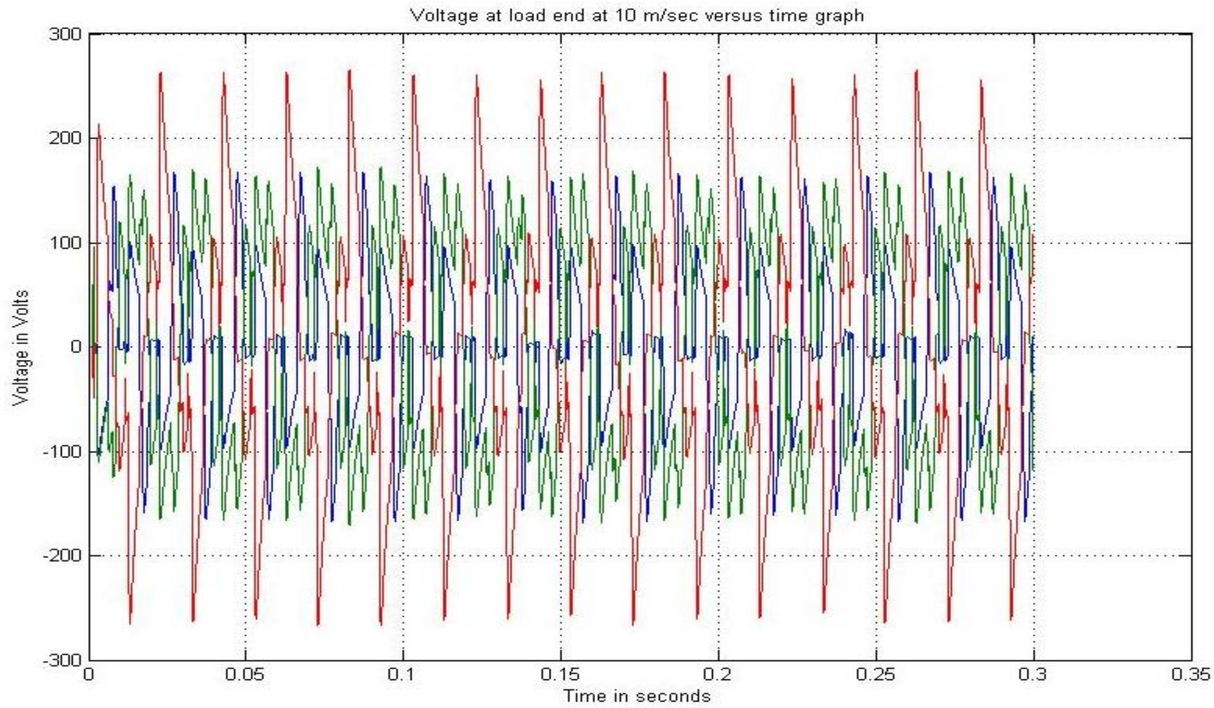

Figure 5.27: Voltage at load end at 10 m/sec wind speed

The voltage at the load end at 10 m/sec wind speed is found to be = 263.5 Volts.

k. Current at load end at 10 m/sec wind speed:- Current = 26.74 A

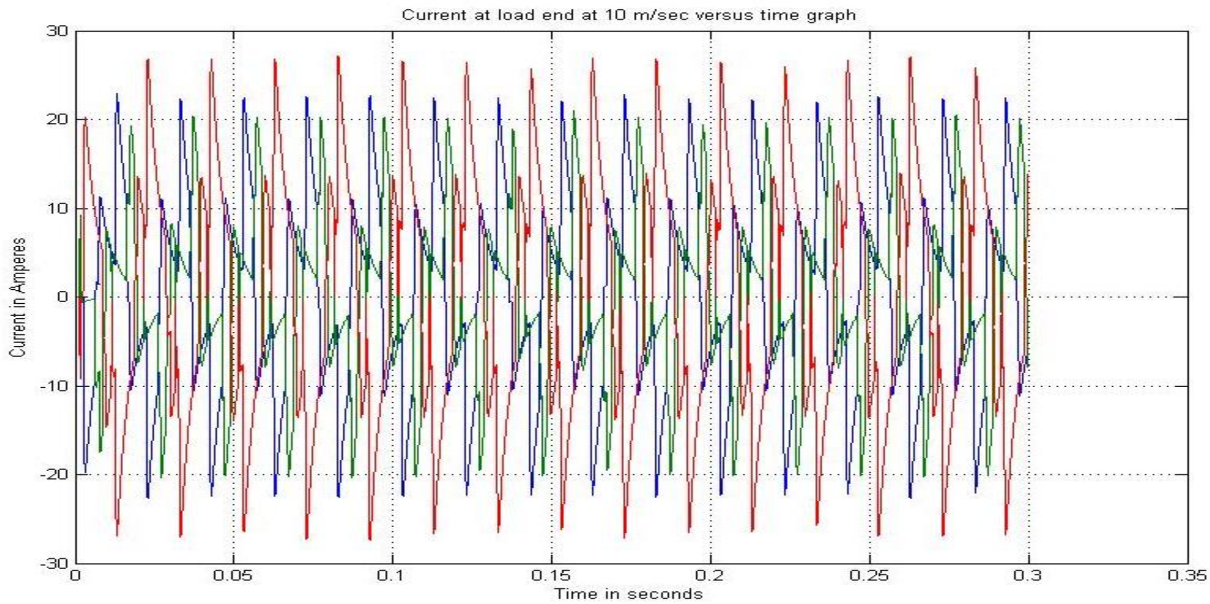

Figure 5.28: Current at load end at 10 m/sec wind speed

The current at the load end at 10 m/sec wind speed is found to be = 26.74 A.

l. Voltage at load end at 8 m/sec wind speed:- Voltage = 263.5 Volts

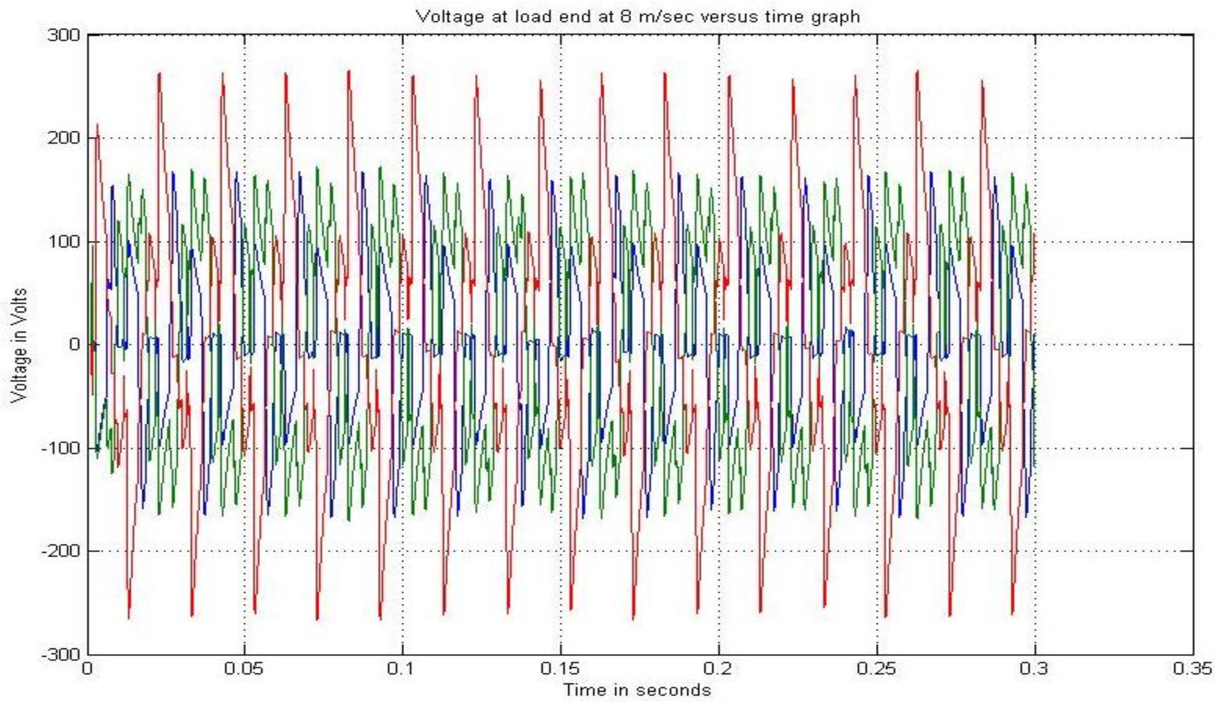

Figure 5.29: Voltage at load end at 8 m/sec wind speed

The voltage at load end at 8 m/sec wind speed is found to be = 263.5 Volts.

m. Current at load end at 8 m/sec wind speed:- Current = 26.74 A

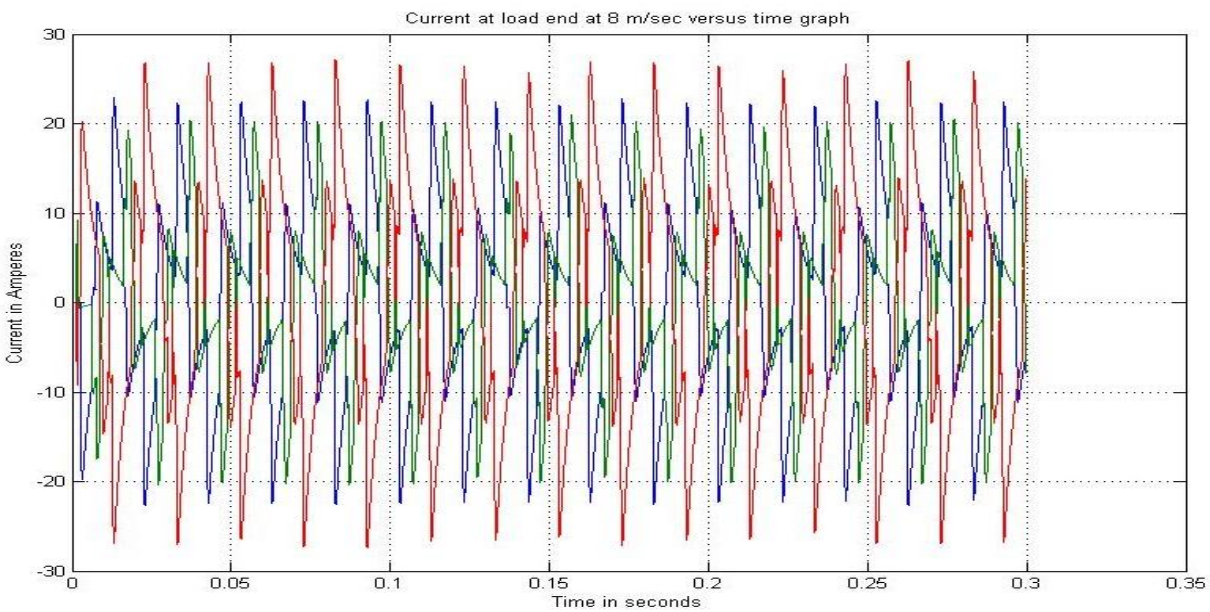

Figure 5.30: Current at load end at 8 m/sec wind speed

The current at the load end at 8 m/sec wind speed is found to be = 26.74 A.

n. Voltage at load end at 5 m/sec wind speed:- Voltage = 263.5 Volts

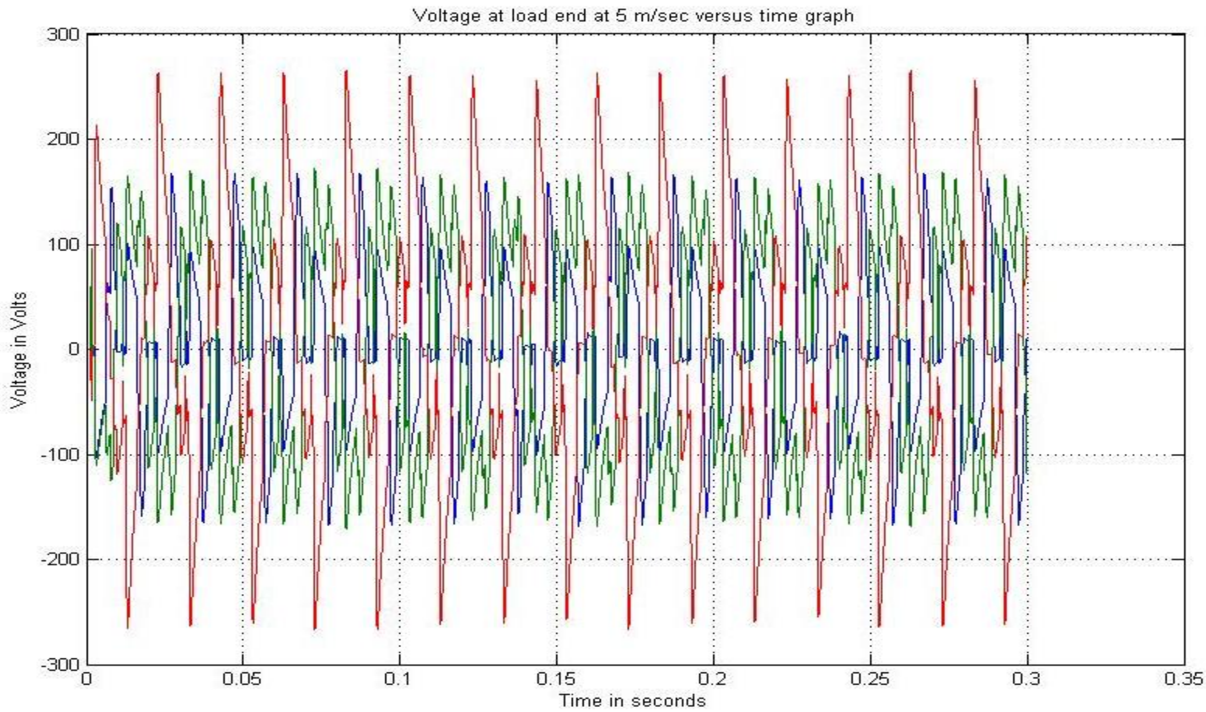

Figure 5.31: Voltage at load end at 5 m/sec wind speed

The voltage at the load end at 5 m/sec wind speed is found to be = 263.5 Volts.

o. Current at load end at 5 m/sec wind speed:- Current = 26.74 A

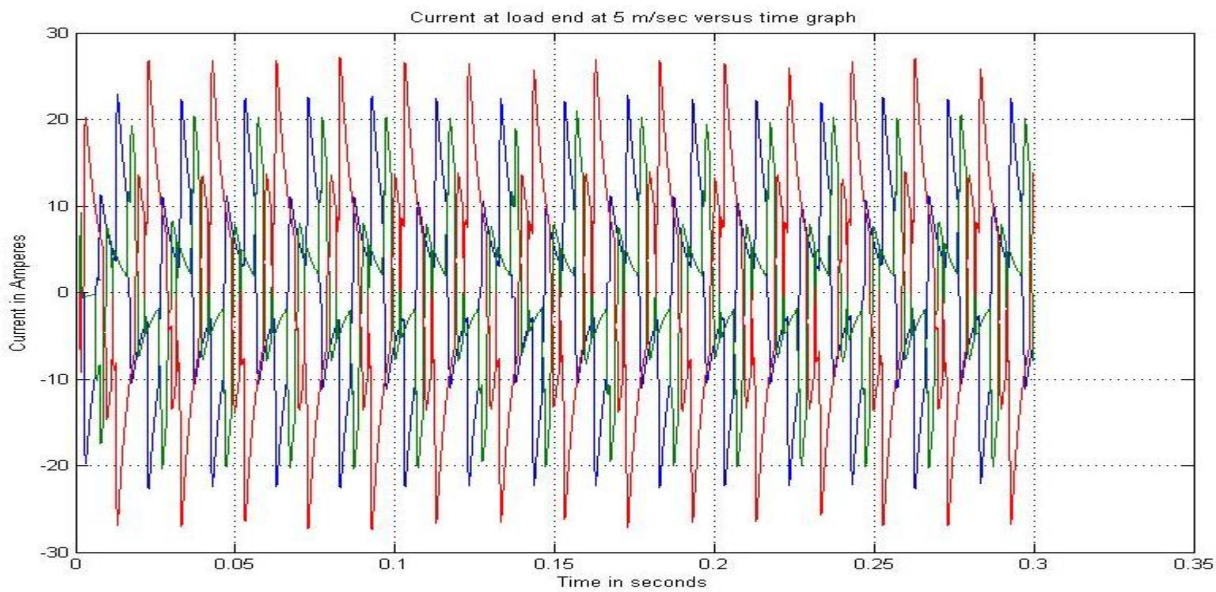

Figure 5.32: Current at load end at 5 m/sec wind speed

The current at the load end at 5 m/sec wind speed is found to be = 26.74 A.

5.7 CONCLUSION

The MATLAB model consisting of PID and PI Controllers with Hybrid Energy Storage Systems (HESS) by using PMSG in RAPS systems is simulated and the observations are recorded and observed. The model is tested for different wind speeds at 12mt./sec, 10 mt./sec, 8 mt./sec and 5 mt./sec. The model is made to run in MATLAB and the observations are recorded and observed. It has been observed that the PI controller has better response characteristics as compared to PID controller. The inclusion of PID and PI controllers with the system has led to improve the RAPS system frequency. Hence, the stability and reliability of the RAPS system has also been improved.

CHAPTER-6

RESULTS

6.1 RESULTS

In this thesis, a lot of work has been carried out by using PMSG in RAPS systems. The Simulink model is made in MATLAB R2013a, 64 bit software and is simulated and the observations are recorded and observed. The model is tested for different wind speeds at 12mt./sec, 10 mt./sec, 8 mt./sec and 5 mt./sec.

From chapter-3, it has been observed that the output voltage of PMSG is 25 KV, which is the nominal voltage required for railway electrification.

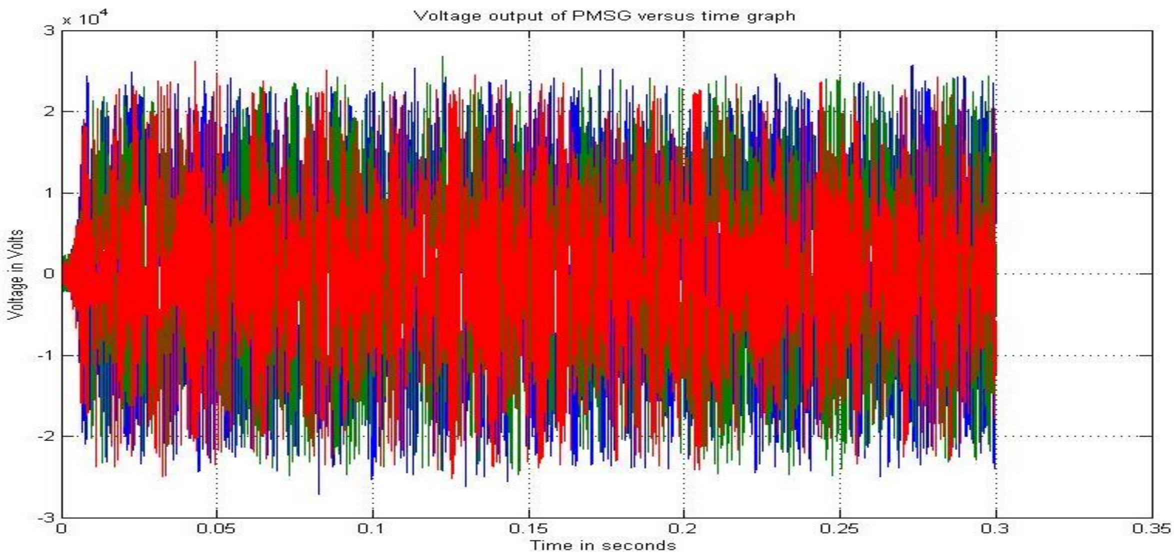

Figure 6.1: Voltage output of PMSG

Here, the Simulink model of HESS is simulated and the observations are recorded and observed. The phase output voltage at the load end is found to be 266 Volts.

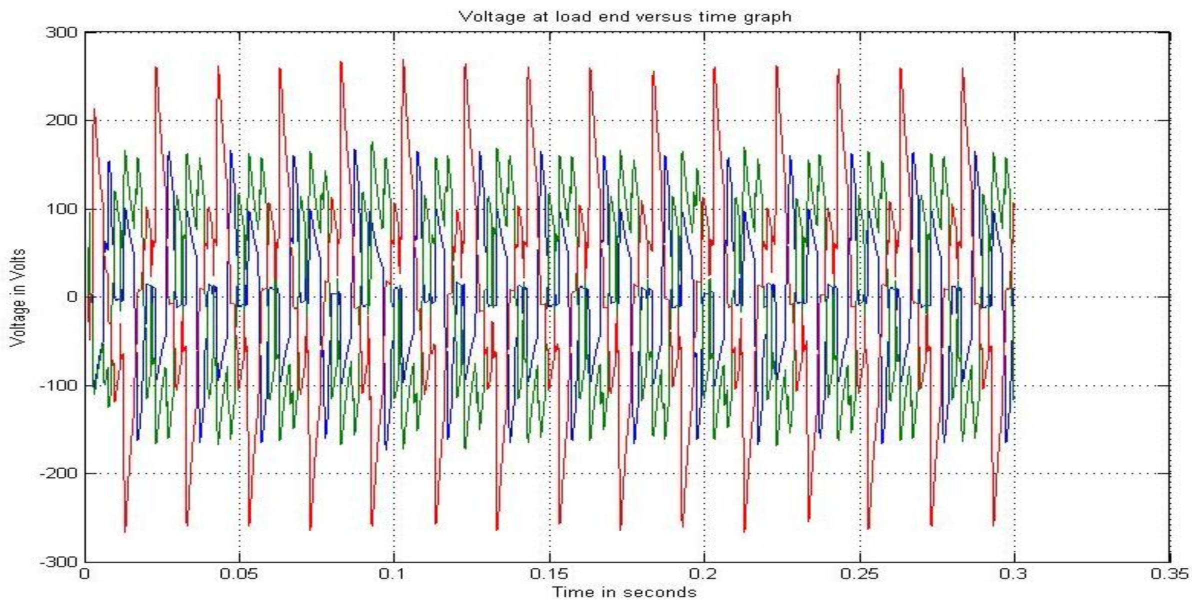

Figure 6.2: Voltage at the load end

In chapter-4, the Simulink model consisting of boost converter with HESS by using PMSG in RAPS systems is simulated and the observations are recorded and observed. The MPPT strategy is applied here. It is observed that the power at the load end is found to be maximum at 4186 Watts at 0.1725 sec.

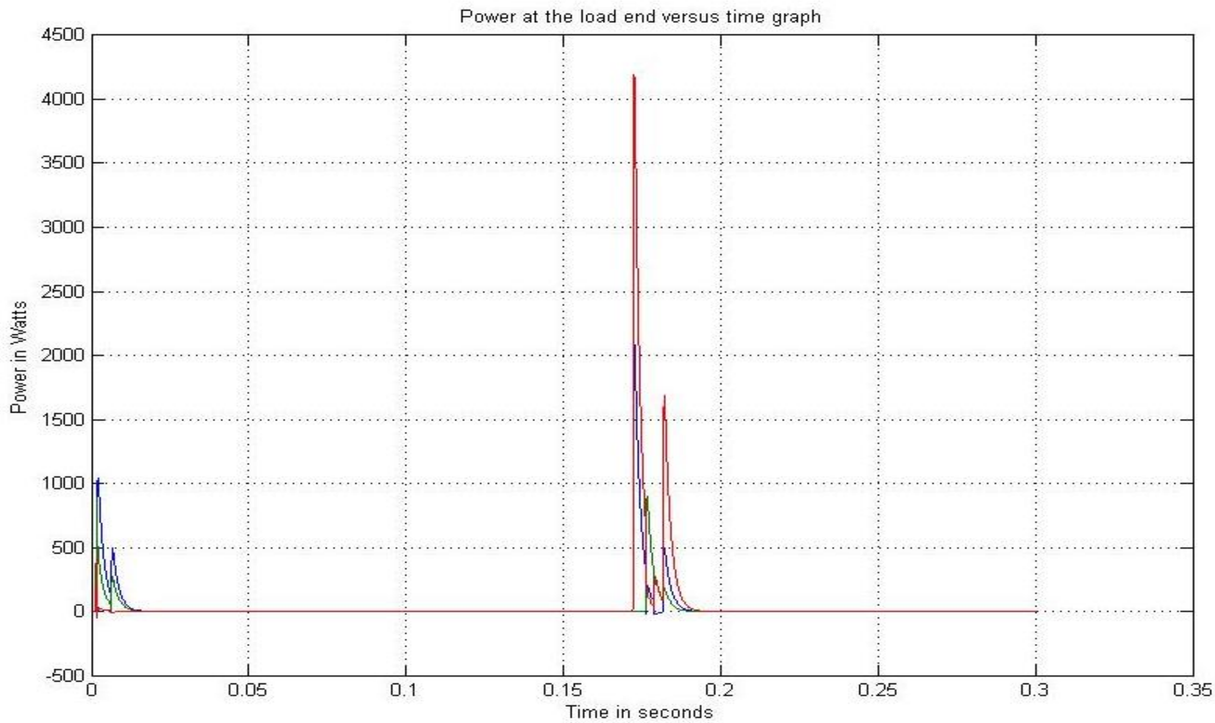

Figure 6.3: Power at the load end

In chapter-5, the Simulink model consisting of PID and PI controllers with HESS by using PMSG in RAPS systems is simulated and the observations are recorded and observed. Using PID controller, the voltage at load end is found to be $2.67*10^4$ Volts and the THD of voltage is found to be 1.85.

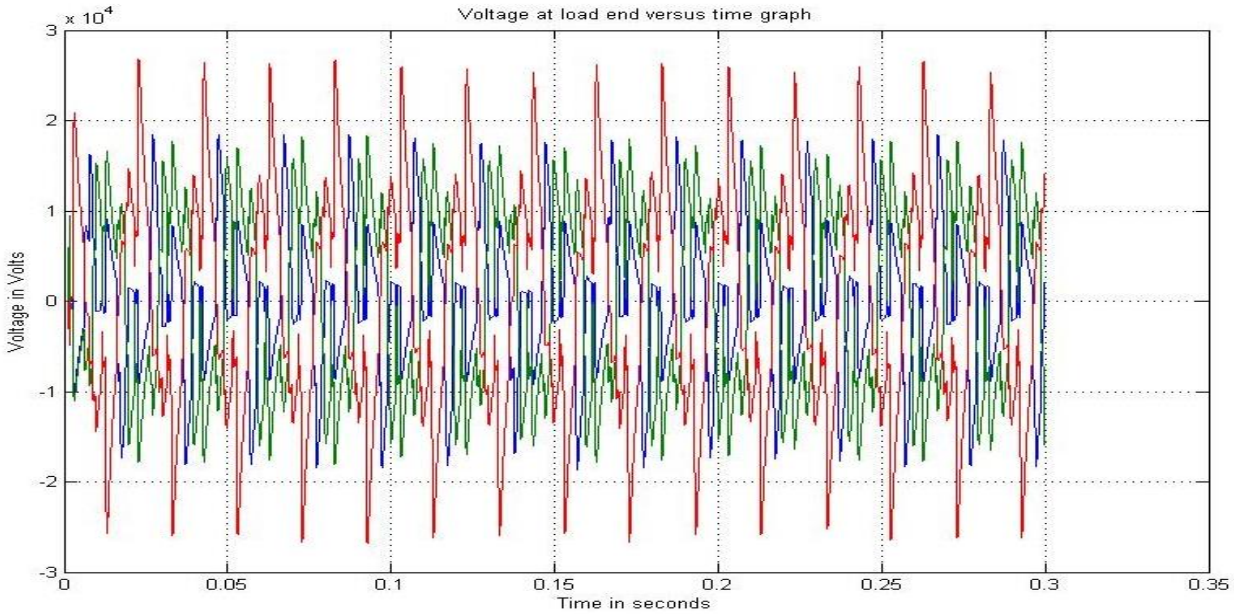

Figure 6.4: Voltage at the load end

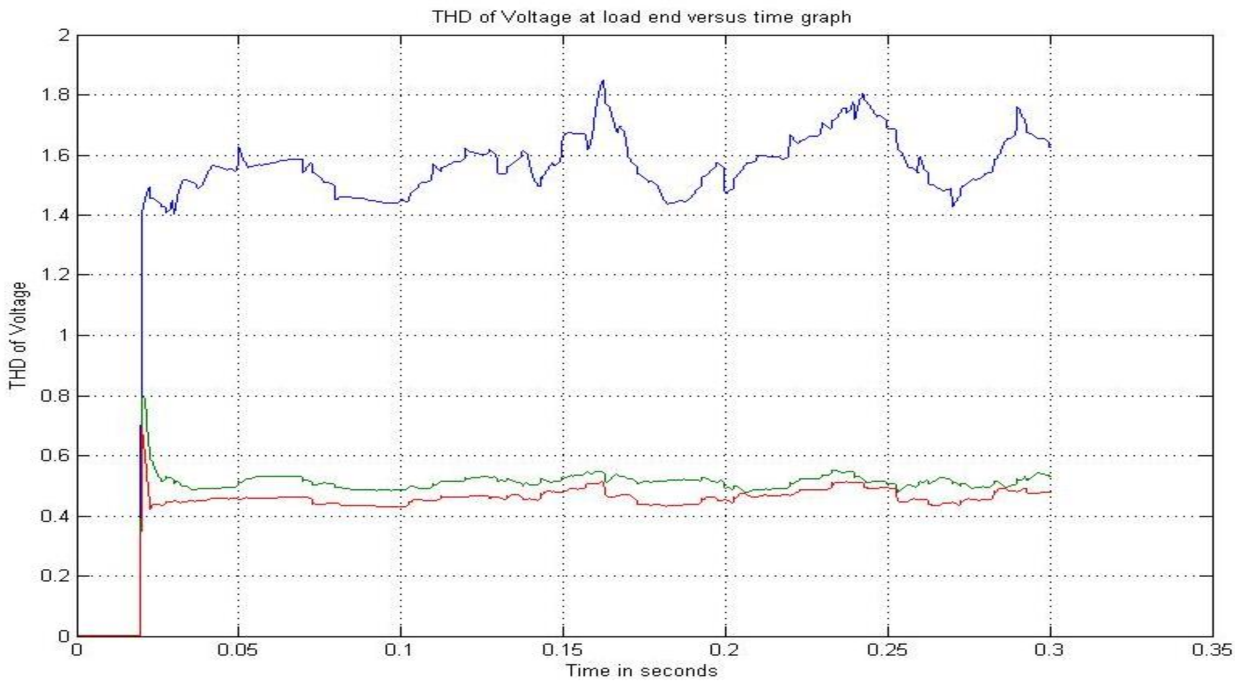

Figure 6.5: THD of Voltage at the load end

Using PI controller, the voltage at load end is found to be 263.5 Volts and the THD of voltage is found to be 1.7611.

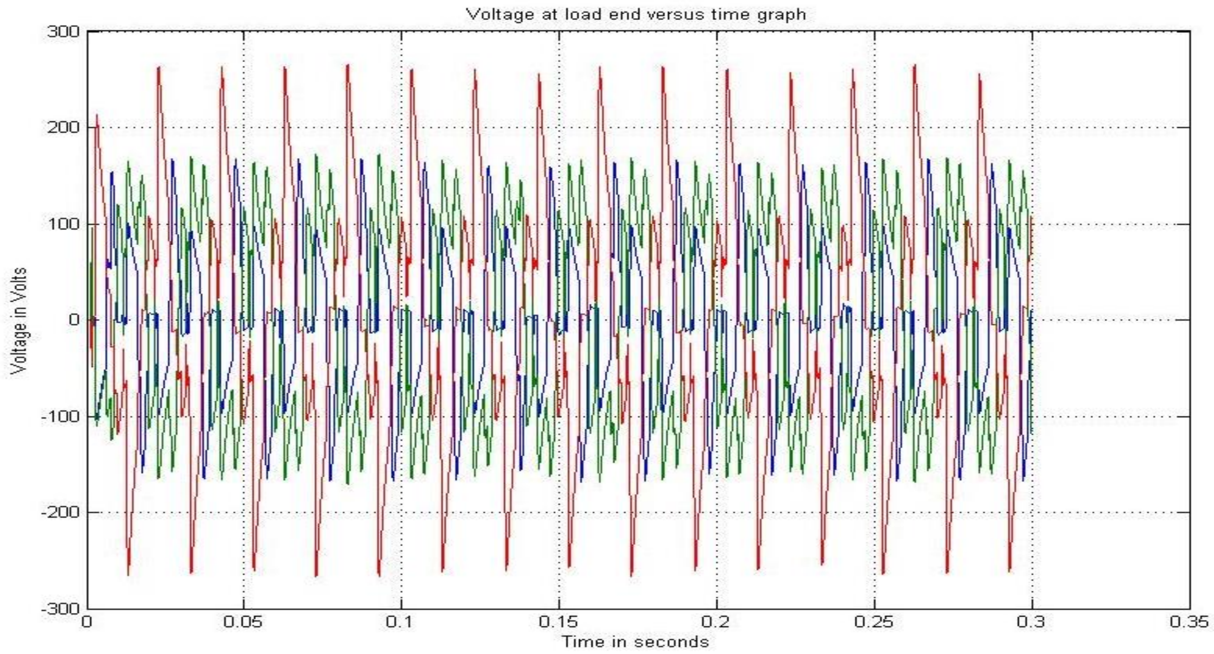

Figure 6.6: Voltage at the load end

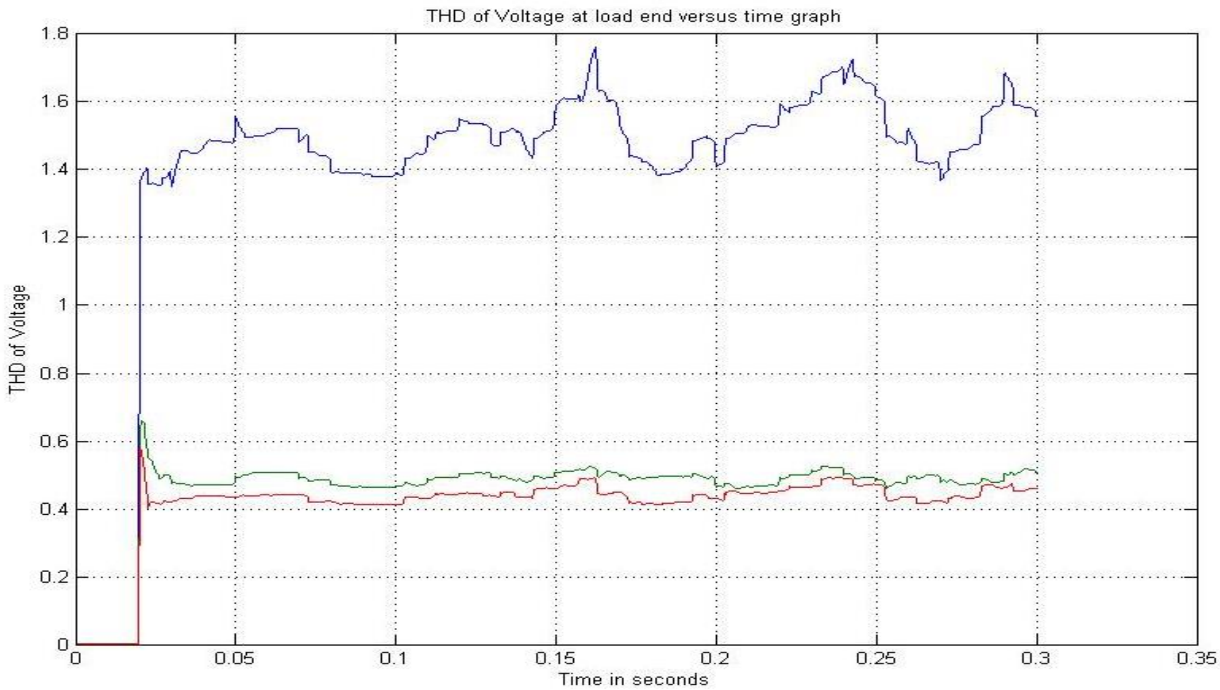

Figure 6.7: THD of Voltage at the load end

The above results are observed and recorded and taken into consideration in this entire thesis work.

CHAPTER-7

CONCLUSIONS AND FUTURE SCOPE OF WORK

7.1 CONCLUSION

This thesis suggests to improve the stability and reliability of the RAPS systems. So, PMSG is used in order to reduce the high expenditure. The RAPS systems are an independent type of network. So, they have gained more popularity.

This thesis also suggests to carry out HESS such as UCs and Lithium-ion batteries to be interfaced into a PMSG based RAPS network to provide the frequency support and improve the stability and reliability of the system. It has been observed that the inclusion of battery and UCs has led the RAPS systems to increase their stability. The reliability of RAPS systems has also been improved. It has also been observed that the output voltage of PMSG is 25 KV, which is the nominal voltage required for railway electrification. So, PMSG can also be used for railway electrification purposes.

This thesis suggests to carry out MPPT strategy in order to deliver maximum power to the RAPS network. A boost converter is used to carry out this strategy. The boost converter with HESS is interfaced into a PMSG based RAPS network. Here, we observe that the power at the load end is found to be maximum at 4186 Watts at 0.1725 sec. So, the maximum power of the Simulink model is found to be 4186 Watts and the maximum power point of the Simulink model is found to be 0.1725 sec.

This thesis suggests to use a PID or PI controller at the inverter or load end of the network in order to enhance the response characteristics. It will finally lead to enhancing the frequency regulation of the RAPS network. It has been observed that the PI controller has better response characteristics as compared to PID controller. The inclusion of PID and PI controllers with the system has led to improve the RAPS system frequency. Hence, the stability and reliability of the RAPS system has also been improved.

This thesis work will help to achieve the goal of eco-friendly electrification.

7.2 FUTURE SCOPE OF WORK

This thesis suggests to carry out HESS with UCs and Lithium-ion batteries to be interfaced into a PMSG based RAPS network. Some energy storage devices may be added in parallel with the HESS network for a PMSG based RAPS network in order to analyze the responses. The energy storage devices may be taken into consideration keeping in view of the stability and reliability of the system.

The MPPT strategy may be applied using buck, buck-boost converters or some other type of converters to analyze the responses. The strategy may be applied keeping in view the stability and reliability of the RAPS systems. Other switching devices like BJT, MOSFET, etc. may be used or taken into consideration along with the converters in order to analyze the responses. Like MPPT strategy, some other control strategy may also be applied for a PMSG based RAPS network.

The frequency regulation of the PMSG based RAPS network may be done using load frequency mechanism, controllers, etc. in order to analyze the responses.

In this thesis, we have used PMSG in an RAPS network. Some other RER may be used instead of PMSG in order to analyze the responses. Some generators may be taken into consideration to analyze the responses. The wind turbine may also be replaced by some other type of wind turbine to analyze the responses. One may take doubly-fed induction generators to analyze the responses.

The entire thesis work will help to achieve the goal of eco-friendly electrification.

CHAPTER-8

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8.2 WEBSITES

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LIST OF PUBLICATIONS

1. Published research paper on “MATLAB simulation of hybrid energy storage systems by using PMSG in Remote Area Power Supply (RAPS)” in International Journal of Electrical and Electronics Engineering Research (IJEEER), ISSN(P): 2250–155X; ISSN(E): 2278–943X, Volume-9, Issue-2, Dec 2019, 43–54 [© TJPRC Pvt. Ltd.].
2. Published research paper on “MPPT strategy for a PMSG based RAPS network using MATLAB” in International Journal of Automobile Engineering Research and Development (IJAuERD), ISSN(P): 2277–4785; ISSN(E): 2278–9413, Volume-10, Issue-1, June 2020, 35–50 [© TJPRC Pvt. Ltd.].

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B.Tech in Electrical & Electronics Engineering (E&EE)	Gandhi Engineering College, Bhubaneshwar	Biju Patnaik University Of Technology (BPUT), Rourkela, Odisha	**2012**	8.08(CGPA) or 75.80%
AISSCE (XII)	Buxi Jagabandhu English Medium School, Bhubaneshwar	Central Board Of Secondary Education (CBSE)	**2008**	77.20%
AISSE (X)			**2006**	79.80%

RESEARCH PAPER PUBLISHED:

- Published research paper on "MATLAB simulation of hybrid energy storage systems by using PMSG in Remote Area Power Supply (RAPS)" in International Journal of Electrical and Electronics Engineering Research (IJEEER), ISSN(P): 2250–155X; ISSN(E): 2278–943X, Volume-9, Issue-2, Dec 2019, 43–54 [© TJPRC Pvt. Ltd.].
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WORK EXPERIENCE:

- Worked as "Assistant Project Manager (Electrical)" in R-Cube Infratech Private Limited, Lucknow, Uttar Pradesh during the time period 14 April 2017 to 01 July 2017. The responsibility was to prepare Estimates (BOQ and Details of Measurements) of Electrical project work as per requirements of our clients-UPSCIDC Limited, Lucknow and C & D.S., U.P. Jal Nigam, Allahabad.
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Date: June 2020

Place: Lucknow **ROHIT SINHA**