Analyzing and Mitigating Power Quality Problems of Grid-Connected Wind Energy Systems

by

Aparupa Das

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Electrical and Electronic Engineering

Khulna University of Engineering & Technology
Khulna 9203, Bangladesh.

April, 2018

Declaration

This is to certify that the thesis work entitled *"Analyzing and Mitigating Power Quality Problems of Grid-Connected Wind Energy Systems"* has been carried out by *Aparupa Das* in the Department of *Electrical and Electronic Engineering*, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

Signature of Supervisor   Signature of Candidate

Approval

This is to certify that the thesis work submitted by *Aparupa Das* entitled " *Analyzing and Mitigating Power Quality Problems of Grid-Connected Wind Energy Systems* " has been approved by the board of examiners for the partial fulfillment of the requirements for the degree of *Master of Science in Engineering* in the Department of *Electrical and Electronic Engineering*, Khulna University of Engineering & Technology, Khulna, Bangladesh, in April 2018.

BOARD OF EXAMINERS

1. ____________________________ Chairman (Supervisor)

Dr. Naruttam Kumar Roy
Associate Professor, Department of Electrical and Electronic Engineering
Khulna University of Engineering & Technology

2. ____________________________ Member

Head of the Department
Department of Electrical and Electronic Engineering
Khulna University of Engineering & Technology

3. ____________________________ Member

Dr. Md. Abdur Rafiq
Professor, Department of Electrical and Electronic Engineering
Khulna University of Engineering & Technology

4. ____________________________ Member

Dr. Md. Rafiqul Islam
Professor, Department of Electrical and Electronic Engineering
Khulna University of Engineering & Technology

5. ____________________________ Member (External)

Dr. Kazi Khairul Islam
Professor & Dean, School of Science & Engineering
Uttara University

Acknowledgement

Fore mostly, I would like to express my sincere gratitude to my supervisor Dr. Naruttam Kumar Roy for his guidance, encouragement, and support throughout the course of this work. It was a valuable learning experience for me to be one of his students. From him I have gained not only extensive knowledge, but also a sincere research attitude. I express my gratitude to Prof. Dr. Md. Shahjahan, Head of the Department, Electrical and Electronic Engineering, who is the backbone of this department and makes all the arrangements and lab facilities for conducting any good research.

I would also like to acknowledge the entire teaching and non-teaching staff of Electrical and Electronic Engineering Department of KUET for establishing a working environment and for constructive discussions.

Finally, I feel a deep sense of gratitude for my parents who formed a part of my vision and taught me the good things that really matter in life. I would like to thank my family members for their support.

Abstract

To meet the excessive demand of electric power and maintain a sustainable development with a greener world, the generation system now moves to renewable energy sources. Among the renewable based distributed generation systems, the wind based one is becoming popular day by day. When the wind based distributed generation (DG) and the distributed network (DN) both are connected to establish a technologically upgraded system, then different types of power quality problems arise in the system. In this thesis, the adverse impact of the resultant harmonics of permanent magnet synchronous generator (PMSG) based wind turbine is examined from every corner and also found a perfect remedy. For pointing out the harmonics nature and magnitude of distribution systems, different types of non-linear loads, such as resistive-inductive loads, induction motor with adjustable speed drive and arc furnace are modeled. In faulty conditions, the voltage sag and swell issues are also overviewed here. In this research, an AC/DC/AC converter is designed with voltage dependent current limiter and the proposed current control mechanism of the generator’s converter is based on the straight line theory. The proposed control mechanism for designing the voltage source converter of the static synchronous compensator (STATCOM), which is connected to a battery, is governed by the pulse width modulation technique. A proper integration between these two control mechanisms creates a stable system and mitigates the power quality problems. The overall performance of the proposed model is tested on a 12 bus radial network, with designed non-linear loads connected to it, using PSCAD/EMTDC software and afterwards laboratory tests are carried out to examine the harmonics currents and voltages. From the analysis, it is investigated that harmonic increases as the number of distributed generator increases and also in faulty conditions. Moreover, the level of harmonic varies based on the position of the wind generator and non-linear loads. The research outcome obtained from this comprehensive analysis proved that the proposed control mechanism approach is successful to eliminate and keep the voltage and current harmonics within a safe range, maintain the power system stability as well as mitigate the voltage sag and swell.

Contents

LIST OF TABLES

LIST OF FIGURES

Figure No	Description	Page
3.10	Model of AC/ DC/AC converter	37
3.11	Breaker operation sequence	39
3.12	Straight line method	40
3.13	Current controller model of AC/DC/AC converter	40
3.14	Model of STATCOM/BESS	41
3.15	Control mechanism of STATCOM/BESS	43
3.16	Model of PLL1 for generating triangular carrier signal	43
3.17	Model of voltage control loop	44
3.18	Model of PLL2 for generating voltage modulating signal	44
3.19	Model of generating switching signal	44
3.20	STATCOM/BESS voltage characteristics	44
3.21	Four quadrant operation mode of STATCOM/BESS	45
3.22	Battery model	46
3.23	12 Bus radial network with wind power based DG	48
4.1	Total setup of the harmonic analysis of a tube light (magnetic ballast)	50
4.2	Total setup of the harmonic analysis of a tube light (electronics ballast)	50
4.3	Total setup of harmonic analysis of a battery supplied inverter with load	50
4.4	Total setup of harmonic analysis of a line supplied inverter with converter and load	51
4.5	Model of induction motor with ASD	52
4.6	Online diagram of an arc furnace	53
4.7	Distorted current waveform due to RL load and DG’s converter	53
4.8	Current waveform with RL load and DG’s converter with STATCOM/BESS connection	54
4.9	(a) Distorted current waveform due to induction motor with ASD and AC/DC/AC converter of DG, (b) Current waveform with STATCOM/BESS	55

Figure No	Description	Page

NOMENCLATURE

N	Harmonic number
A_n	Amplitude of nth harmonic component
A	Exponential zone amplitude
T	Length of one cycle in second
I	Current
V	Voltage
V_w , W_s, $V_{\text{cut-in}}$	Velocity of wind
W, W_m	Mechanical rotation
B	Pitch angle of turbine blade, Exponential zone amplitude
P_g	Power of wind turbine
E	Kinetic energy, No load voltage
E_0	Battery constant voltage
M	Mass (kg)
A	Swept area (m^2)
C_p	Power co-efficient
R	Radius of the blade
T	Time (s)
x, s	Distance (m)
$\frac{dm}{dt}$	Mass flow rate (Kg/s)
$\frac{dE}{dt}$	Energy flow rate (J/s)
F	Force (N)
P	Air density
P_r	Pressure (mm of Hg)
VP	Vapor pressure of water (mm in Hg)
T	Temperature (K)
K	Polarization voltage
Q	Battery capacity
$\int idt$	Actual battery charge
X	Reactance
R	Resistance

ABBREVIATIONS

PMSG	Permanent Magnet Synchronous Generator
GHG	Green House Gas
UNGA	United Nations General Assembly
SDG	Sustainable Development Goal
FSWT	Fixed Speed Wind Turbine
VSWT	Variable Speed Wind Turbine
DFIG	Doubly Fed Induction Generator
DN	Distribution Network
DG	Distributed generation
DVR	Dynamic Voltage Restorer
STATCOM/BESS	Static Synchronous Compensator With Battery Energy Storage system
ARENA	Australian Renewable Energy Agency
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
PLC	Programmable Logic Control
ASD	Adjustable Speed Drive
FACTS	Flexible Alternating Current Transmission System
SVC	Static VAR Compensator
TCSC	Thyristor Controlled Series Capacitor
SSSC	Static Synchronous Series Compensator
CFL	Compact Fluorescent Lamp
HPF	Hybrid Passive Filter
DSTATCOM	Distributed Static Synchronous Compensator
VSC	Voltage Source Converter
FFT	Fast Fourier Transform
LG	Single Line to Ground Fault
LLLG	Three Phase Fault
LLG	Double Line to Ground Fault

CHAPTER I

Introduction

1.1 Background

Standing on this turbulent time-zone, it can be certainly said that no development today can be achieved without energy. Our inclination to technology has tightened our fists so strongly that people now become crumbled in the absence of energy, even for a single moment. However, it has become a critical problem to generate such high magnitude of energy for maintaining this energy demand of the whole world without hampering the environment. To mitigate this high demand of power, fossil fuel is being used as an important but a deleterious source. Because the excessive use of fossil fuel emits gigantic amount of carbon-di-oxide, sulphur-di-oxide, lead, and other heinous gases that are extremely detrimental to our health. These gases are commonly known as greenhouse gases (GHG), which are not only increasing health risks but also taking the whole world towards a critical environmental disaster [1], [2]. The global temperature has risen to a drastic level as the amount of GHG is increasing in the atmosphere. If this trend goes on, the world will be doomed very soon. The scientists, academics, researchers, planners as well as the world leaders must address this critical issue with great care and a suitable and effective alternative must be introduced and renewable is the ultimate solution [3], [4]. In 2015, the global communities like G-20 and G-7 focused to adopt the renewable energy sources. Another important matter is, the United Nations General Assembly (UNGA) has adopted SDG (Sustainable Development Goal) that describes “Sustainable energy for all” (SDG- 07).

The current buzz, renewable energy, is the most effective solution for sustainable power generation. This very essential energy could be generated from a wide range of sources like solar radiation, wind, hydro, thermal and many more. The advantages of this renewable energy are too many to describe in words, but the common benefits are, it is abundant in quantity, worldwide available, does not pollute the environment and so on. Among the various sources of renewable energy, this research has focused on the use of wind power. Recent researches are very much enthusiastic about the wind energy and its efficient utilization as wind turbines are easy to construct, free, safe, do not cause air or water pollution and the land of the wind farms can be used for other purposes [5]. However, the first known practical windmills were built in Sistan, a region between Afghanistan and Iran, from the 7th century [6]. The first automatically operated wind turbine for electricity production in Cleveland, Ohio, built in 1887 by Charles F. Brush [6]. Wind power is generated by the conversion of the kinetic energy of the moving air to the mechanical energy and afterwards, the mechanical energy is converted to gain the electrical power. The working principle of a wind turbine is opposite of a fan. Like a fan it does not use electricity to produce wind, rather the wind turbine uses wind to generate electricity. Current available turbines with shafts can capture only 40%-50% of the total available energy. These wind power plants generally can produce 5-300 MW, though plants of higher and lower capacity are also seen [7], [8]. With the development of wind technologies, the trend of using the fixed speed wind turbine (FSWT) is shifted towards the variable speed wind turbine (VSWT) to utilize the aerodynamics of the wind more significantly within a wide range of wind velocity and to maintain the stable torque [9]-[11]. However, the VSTW generators can be categorized into two categories as doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG). After comparing DFIGs and PMSGs, it is found that PMSGs are optimum in generation with wide range of varying wind speed and enhance the grid efficiency. The PMSGs have other benefits like low loss, stable and comparatively high magnitude of power is generated from it [12], [13].

When the issue of establishing a power distribution network (DN) system with renewable power sources arises, then the distributed generation (DG) comes forward spreading its support to mitigate the problems. The DG system is a method of producing power from a small-scale energy source which is fed to the DN directly. Sometimes this DG system is called as decentralized energy generation system or onsite generation. The conventional or centralized power system are often required to cover a long distance to transmit electricity which increases the transmission loss as well as the cost and these problems are often highlighted in power distribution sector. To minimize such situations, DG system is the perfect solution [14], [15]. The DG system is connected to the DN for giving sufficient power support which enhances the power reliability. This DG contributes in the application of competitive energy policies, diversification of energy resources, and reduction of on-peak operating cost, lower losses, lower transmission and distribution costs and so on. Moreover, nowadays, the roles of DN are changed a lot because of DG system. Traditional DNs are only used for delivering electricity to the customer whereas recently, DNs are using for power collections from different DGs. Though DGs have several advantages but they increase the level of harmonics in the DN, because they use power electronics converters in the grid connected system for voltage and frequency issues. Moreover, the uses of non-linear loads in DNs are increasing day by day and they also contribute to the harmonics distortion.

1.2 Research Motivation

Power quality problems such as harmonics, voltage sag, swell etc. are increasing day by day. Harmonics are mainly introduced in the system due to the non-linear loads and in this modern world the use of non-linear loads are dramatically increased. Previously, various researches have done for analyzing and calculation of the level and nature of harmonics which only deals with non-linear loads [16]-[19]. They have found different solutions for different loads like, harmonic reduction of the florescent lamp is done through the technique of splitting the distribution transformer into two transformers through secondary winding and the neutral conductor is shared by the two transformers where a LC filter is added to the neutral conductor. This technique is only used for florescent lamp. So by this process, other non-linear loads cannot get relieve from the curse of harmonics. Moreover, researchers have found different sorts of solutions like various compensators, filters, supercapacitor, magnetic flux compensation, current injecting methods and so on [20]-[22]. However, the most popular current injecting methods sometimes are not able to suppress the lower order odd harmonics (3rd, 5th, 7th) effectively [23]. These traditional methods only deal with the harmonics reduction but they cannot deal with the other power quality issues like voltage sag, swell which may damage equipment connected to power system. Device like dynamic voltage restorer (DVR) can be a solution of voltage sag. However, it is unable to remove harmonics. So there is a research gap always been here and it is essential to find a prefect remedy which will deal with the solution of all the power quality issues i.e. harmonic, voltage sag, swell, power stability at a time and this is the main aim of this research to solve all problems by using only one device. Moreover, the harmonic issues related to DG connected DN are not extensively studied yet. Before integrating large-scale power electronics interfaced DG into existing DNs, the problems must be precisely understood and critically analyzed. The research wishes to put light on the problems associated with such systems and finds a perfect remedy and set a way to popularize wind farm based DGs to ensure a sustainable world.

1.3 Thesis Objectives

The aim of the thesis is to design such control systems which will take the current wind based power system to a new dimension and identify the power quality problems and a perfect solution of the DG connected DN system under different conditions with a superior DG model. The objectives of the entire model are given below:

- The research aims to develop a highly effective wind based DG that can be a token of the upgraded wind power generation system with PMSG.
- The power converter is a paramount component for maintaining constant voltage and frequency and this converter will be designed with advanced current control mechanism which is governed by voltage dependent current limiter based on straight line theory and thus system will generate less harmonics.
- Design a static synchronous compensator with battery energy storage system (STATCOM/BESS) with proper control mechanism based on pulse width modulation (PWM) technique and this will be used to eliminate lower order odd harmonics which are most detrimental for the system.
- A proper integration among these upgraded control mechanisms will be established to create a stable system.
- Power quality problems of DG integrated DN are disclosed from every corner and calculated the generation of harmonics with respect to number of DG, position of DG and in presence of fault.
- Stabilization of reactive and active power and mitigation of voltage sag and swell will be considered at the same time when the maximum amount of harmonics will be suppressed.

- Finally modeling will be done to create such a system where extra filters and compensating devices will not be necessary and only STATCOM/BESS can deal with all the associated problems, which will not only save the cost but also minimize the space and ultimately simplify the design of the system.

1.4 Organization of Thesis

The whole thesis is divided into five chapters including introduction and each chapter is organized in the following way.

Chapter 2 carries the literature review part regarding important factors of this thesis like wind system, DG, DN, FACTS devices, power quality problems. This chapter also contains various research works related to it, which is previously done and this will help to identify the present research gaps and limitations.

Chapter 3 deals with methodology and modeling part. In this section, the wind-based DG model and the converter models are given in detail. The STACOM/BESS model and The DN model are also a part of this section.

Chapter 4 is the power quality problems and solutions part. In this chapter, simulation results are given. Moreover, a comparison among proposed model and other technologies are given. It also contains the non-linear load models and experimental results conducted in laboratory.

Chapter 5 presents the conclusions of the work along with the future scope followed by references.

CHAPTER II

Literature Review

2.1 Introduction

Now the high time has come to shift towards renewable sources based power generation system. Many researches have already been done to understand the future needs with modern approaches. This research contains the power quality issues of wind system. In this regard, various papers, research articles and reports have been taken into account to better understand the current situation and its future prospect.

2.2 Renewable Energy

Renewable energy has become the talk in the time. The world today is very much concerned with sustainable development. It is proved that without sustainable development, it would be very much difficult to keep the harmony at every sphere of life, environment and total universe. So time has come to embrace renewable energy for the wellbeing of the whole world.

Australian Renewable Energy Agency (ARENA) defines [24], "Renewable energy" as "Renewable energy is the energy which can be obtained from natural resources that can be constantly replenished".

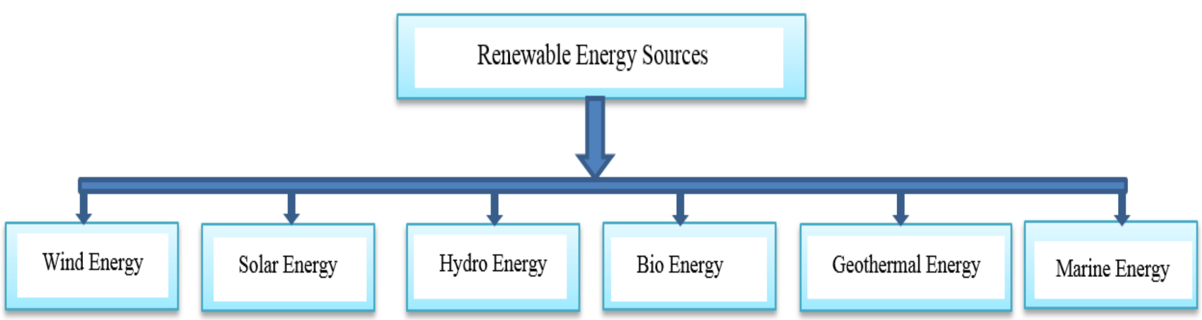


Figure 2.1: Classification of renewable energy sources.

In this world, there are different kinds of renewable energy sources from where it is possible to avail renewable energy or green energy. However, it is commonly well known with six types of renewable energy sources (given in Fig. 2.1).

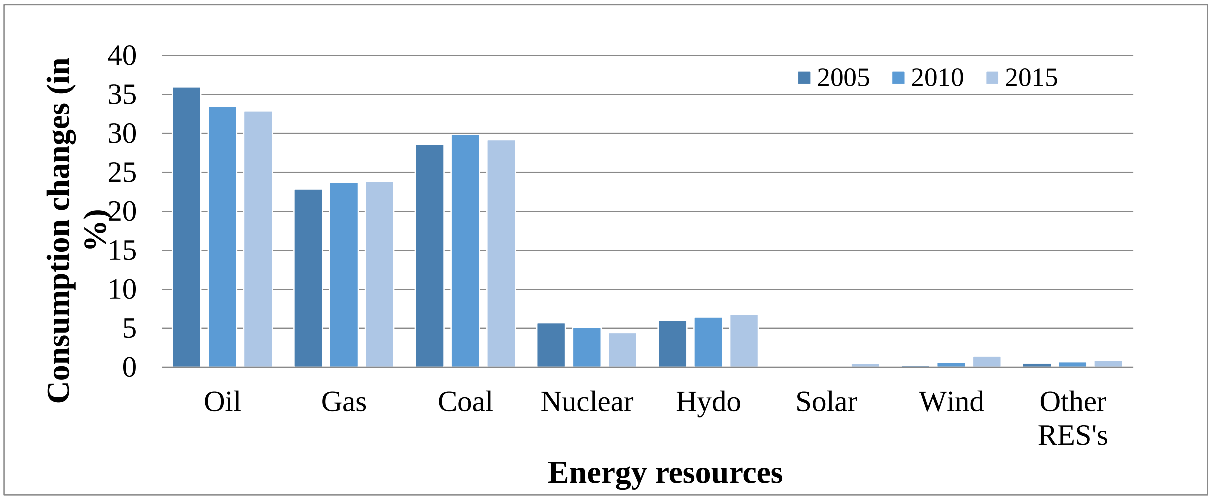


Figure 2.2: Analysis of consumption changes (in %) in energy market of fossil fuel and renewables from 2005 to 2015.

It has become a key component to use renewable energy resources throughout the world to combat the climate change, reduce hazards and pave a way towards sustainable developments. In the past, the fossil fuel was more cost effective than the renewable energy. However nowadays, it is a matter of hope that cost benefits of the fossil fuel over the renewable energy is being minimized day by day. From the following comparative analysis the facts can be understood (Fig. 2.2) [25]. From this Fig. 2.2, it is observed that the consumption of oil is decreased day by day whereas the consumption of renewables like hydro and wind are following the increasing trend. From this study, it is also clear that the popularity of wind is rising.

2.3 Wind Turbine

Nowadays, the wind energy sector has become very popular in the whole world. There are many reasons behind it. First of all, the wind turbine has low environment impacts. It takes a little amount of land for its construction. It may emit a very tiny amount of GHG at the time of installing but there is no emission harmful gas at the time of operation. It reduces the net amount of pollution. Recent technologies have made the blade rotation of the turbine slow and silent. It does not hamper the free movement of birds [26]. Recently, the blades are located in the upwind rather the lower wind. As a result the level of infrasound is minimized. Scientists and authorities prove that there is no risk due to the low infrasound [27].Wind turbines are mechanical devices that converts the wind energy to mechanical energy and afterwards mechanical energy is converted to electrical energy. Commonly, there are two types of wind turbines [36] one is vertical axis wind turbine (VAWT) and another one is horizontal axis wind turbine (HAWT). In VAWT, the shaft is mounted vertically to the ground like an eggbeater. The Darrieus wind turbine is the most common vertical axis turbine. In 1931, French engineer Georges Darrieus designed this model [28]. Naturally the main benefit is that the VAWT does not have to be attached top in the sky to catch more wind speed to generate power. The VAWT can start to generate power at a low speed than the HAWT, therefore it can be mounted lower that other wind turbines generally would be mounted [29]. Also, VAWTs do not have to change the directions to get the wind [30]. The VAWT also spins quieter than the HAWT. This makes it ideal for presentations that do not need much power but delivers just enough to power the loads. The drawbacks is, the VAWT usually deliver low power and low efficiency than HAWTs because blades have more drag in this type [31]. The most easily found wind turbine is horizontal axis. The advantage of the HAWT is that it has a variable blade pitch. The HAWT has the uppermost effectiveness as it takes power from the total blade revolution. The drawback of the HAWT is that it needs quicker wind speeds to start generating adequate power. These types of wind speeds are generally get at the high. Therefore, the HAWTs have to be fixed on the high and tall towers to improve the power efficiency and to allow this to catch the adequate wind that is required to work properly. Other drawback of this types that it depends on the direction of the wind [31].

Wind turbines have three important parts that are: nacelle, rotor and tower, as shown in Fig. 2.3. The nacelle is the main mechanical compartment of the wind turbine. It has gear box, brake or controlling mechanism and generator. The controlling mechanism increases the energy collection and conversion. A shaft connects nacelle with the rotor hub. There are three (usually) wing-shaped blades known as rotor. The rotor is connected with the central hub. The wind strikes the rotor and then it starts moving. Therefore, the wind's kinetic energy is captured by the rotor and is turned into the rotational energy. The total system is established on a strong foundation and it is made enough high so that the blades can gain necessary wind resources. This system requires a conduit to transfer electricity generated from the wind turbine to the collection system. Generally, the whole amount of the electricity is transferred to the national grid. According to the location, wind farm can be classified into two types: one is on-shore and another is off-shore. When the wind turbine is located on land it is called on-shore whereas, offshore wind farm is constructed off-shore (sea or freshwater). In general, the maintenance cost of the off-shore wind turbine is 20% higher than the on-shore wind turbine [32]. The main disadvantage of the on-shore wind farm is, it needs back up supply in the time of insufficient wind strength.

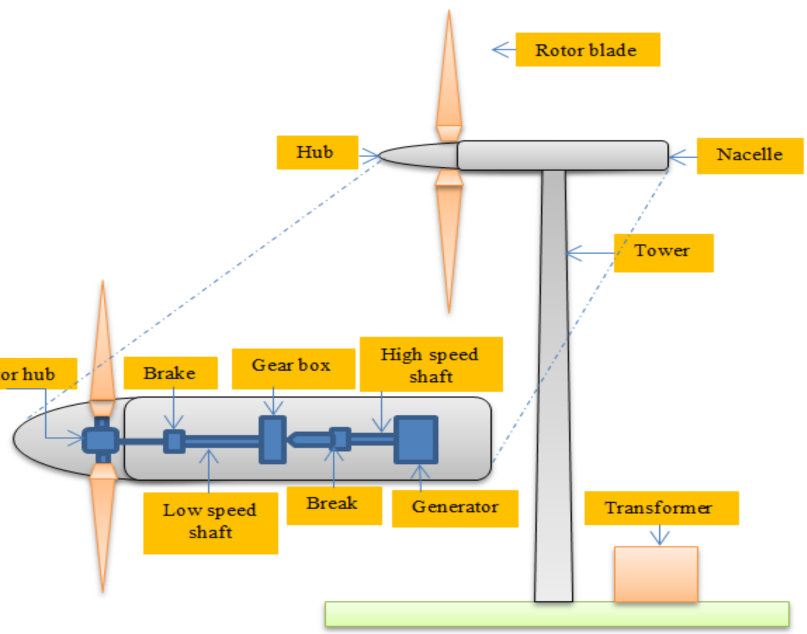


Figure 2.3: Energy conversion of typical wind turbine.

Wind Turbine technologies have already upgraded from the past. Clipper, Mitsubishi, Gold Wind, General Electric, all these renowned wind turbine manufacturers wish to design their future projects in the 10-15 MW class [33]. Global manufacturers are relying on multi-MW turbines. From statistics, it is be seen that 2.5 MW wind turbines and above rated ones covers 18.5% of all 2014 installations [34]. When the grid connected wind generators become popular, researches are doing many researches on various wind generators with different power converters. PMSGs recently catch the eyes of the industries and manufacturers. This technology ensures high-power density and reliability, reduces the want of gear box and exciters, low rotor loss and lastly high efficiency [35].

2.4 PMSG

The recent wind generation systems around the globe are following the trend of using PMSG and global companies are inclining towards PMSG [34].The statistical analysis forecast the fact that manufacturers and industries are moving towards wind turbines with PMSG rather wind turbines with DFIG. Previously generators use exciters like coils but recent advancement avoiding exciter uses permanent magnet. The permanent magnet in this generator is mounted to a shaft. When the system is at work, then the rotor and the magnetic field of the stator have the same angular speed and the electricity is generated at the stator end. At the center of the assembly of the generator, there is a rotor having a permanent magnet with it. And there is a stator at the end, which is a stationary armature and connected with the load or demand side. The voltage of the machine will be determined by the supplied load. If the load is inductive, the angle between rotor and the magnetic field of the stator is more than 90 degree, then the generator increases voltage and it is termed as the over excited generator and on the other hand, if the load is capacitive then the generator becomes the under excited one.

The armature is built with a set of three conductors which supplies the three phase current. The difference between the winding of the phases is 120 degree. The three conductor generates magnetic field in such a way that it seems the whole set of conductors are a single rotating magnet generating uniform torque. The magnetic field of the stator is steady rotating field which will rotate at the same frequency with the rotor. The frequency (Hz) of the stator is directly proportional to the speed (RPM) of the rotor. In the PMSG system, the magnetic field produced in the rotor is because of a permanent magnet but other than PMSG, the winding of rotor with dc current supply along with brushless exciter or slip ring assembly is used to produce magnetic field. So, the assembly becomes easy and cost effective. But it is difficult to use control the voltage of the PMSG because air-gap flux generated in this system and this is a disadvantage. The air gap flux causes core saturation. On the other side, PMSG increases safety, easier to assembly than the conventional generators, cost effective and produces comparatively high magnitude of power for the system. All these reasons make the PMSG system convenient to use and popular for the large scale generation of power. PMSGs are now being designed with multi-phase facilities and distributed converters, which increases power handling capacity [36]. PMSGs have winding that provide inherent electric isolations [37]. This winding helps the PMSGs to suppress circulating current. PMSGs also have phase shift between the windings. This phase shift helps to cancel the lower order harmonics.

2.5 Power Converter

By the use of these highly effective power electronics devices in wind power system, the variable speed operation of the wind turbine with advanced dynamic control and steady-state conditions of the wind generators, was become possible. There are various types of converter are used with the PMSG [38]. They are classified as:

2.5.1 Thyristorised Grid Side Inverter

The output of ac side of the PMSG is changed into dc by applying any of the given converters and then again changed to ac by applying thyristorised inverter connected to the grid. This topology can be again classified into following types:

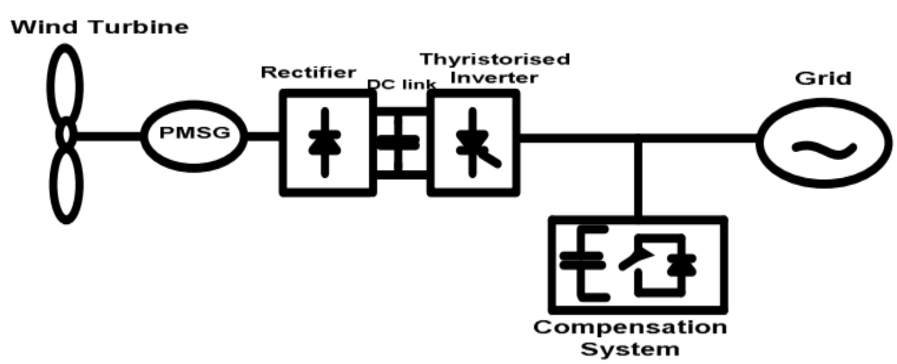


Figure 2.4: PMSG with uncontrolled rectifier, grid side thyristoried inverter and compensator [38]

a) Generator Side Diode Rectifier: The output of the PMSG is rectified with the help of an uncontrolled rectifier to form a dc link [39]. A line commutated thyristorised inverter converts the dc power into ac and coupled with the grid as shown in Fig. 2.4. The advantages of this topology as compared to the hard-switched inverters are reduced cost and higher available power rating.

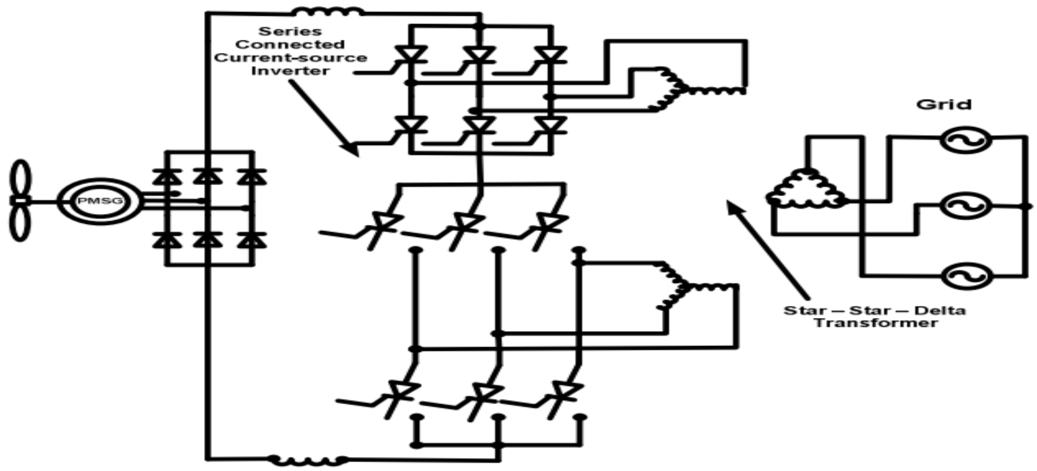


Figure 2.5: PMSG with diode rectifier and series connected thyristorised CSI bridges [38].

b) Generator Side Diode Rectifier with Series Connected Thyristorised Current Source Inverter (CSI) Bridges: In this topology the generator output is rectified by an uncontrolled rectifier and fed to two series connected thyristorised CSIs shown in Fig. 2.5. The output of CSIs are fed to the grid through a three winding transformer (star-star-delta). This topology is useful for large multi-megawatt wind turbines [40], [41].

2.5.2 Hard Switched Grid Side PWM Converters:

The following topologies are being used with the grid side PWM converters.

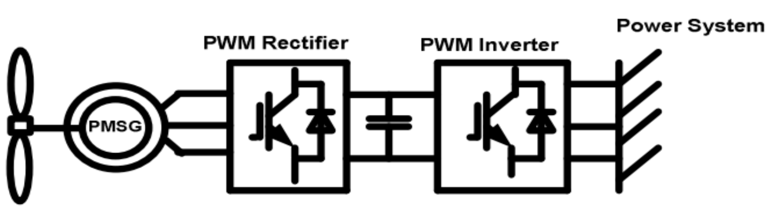


Figure 2.6: PMSG with back to back PWM converter [38].

a) Back to Back PWM VSI: In generator side converter is controlled to extract maximum power under different wind conditions and grid side converter is controlled for power factor regulation, as shown in Fig. 2.6 [42]. A chopper circuit is used for the stable operation under the line fault condition and the output power smoothening is achieved via coordinated action of dc link voltage and pitch angle control of wind turbine [43], [44].

b) Generator Side Phase Shifting Transformer feeding Series Type 12 Pulse Uncontrolled Rectifier (Fig. 2.7): At the generator side passive filters and phase shifting transformer feeding series type 12 pulse rectifier gives high efficiency results and can suppress the distortions present in the PMSG output voltages and currents [45]. The output of the rectifier is inverted into ac voltage of desired magnitude and frequency and fed to the grid by PWM inverter. A grid side filter is also used.

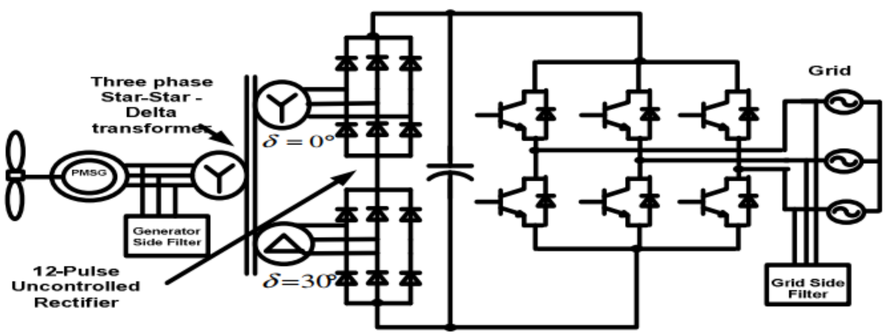


Figure 2.7: PMSG with phase shifting transformer feeding series type 12 pulse uncontrolled rectifier [38].

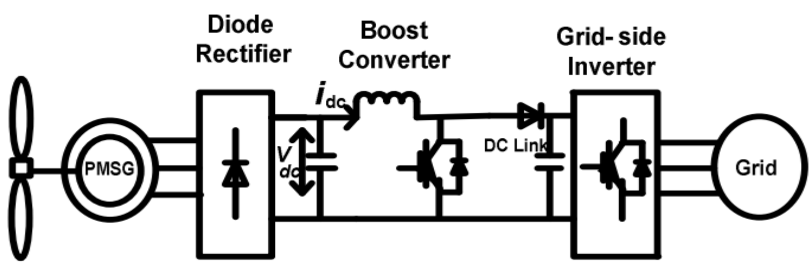


Figure 2.8: PMSG with uncontrolled rectifier and boost converter [38].

c) Generator Side Uncontrolled Rectifier with Boost Converter (Fig. 2.8): The output of the generator is rectified by an uncontrolled rectifier and the maximum power point tracking is achieved through a boost converter [46]. The advantage of the technique is that no wind speed measurement is required.

2.5.3 Multilevel Converters

In order to connect power semiconductor switches directly to medium voltage grids, a new category of multilevel inverters have been developed [47], [48]. Three different topologies of multilevel inverters are popular: diode-clamped (neutral-clamped); capacitor-clamped (flying capacitors); and cascaded multi-cell with separate dc sources.

a) Flying Capacitor: Three-level flying capacitor converter with carrier phase shifted SPWM technique has shown in Fig. 2.9 [49]. Its advantages are that the real and the reactive power flow can be controlled, due to the presence of large number of capacitors. The disadvantages of this topology are: pre-charging of the capacitors to the same voltage level is required, large number of capacitors makes the system bulky and expensive, balancing control of flying capacitor voltages is required.

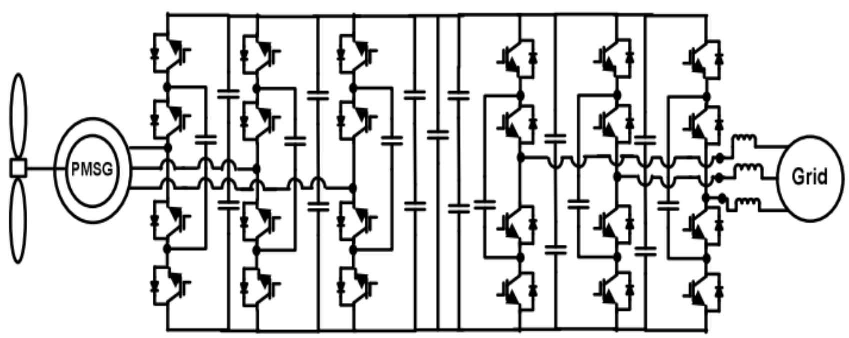


Figure 2.9: PMSG with flying capacitor multilevel converter [38].

b) Neutral Point Clamped (Fig. 2.10): The switch-signal phase delay control has been implemented for neutral point potential balancing of three level inverter based on the characteristics of boost three level chopper [50].

c) Cascaded H Bridge: Offshore wind farms is the latest trend in wind power generation. In an offshore application to avoid copper loss, a step up transformer is included in the nacelle of wind turbine along with the generator and converters. But it increases the mechanical loading of the tower. In order to have a transformer less design a multilevel cascaded voltage source converter has been developed to generate high ac voltage [51]. The dc link voltage in each module is obtained by the rectification of output voltages of two isolated generator coils. An

H-bridge inverter converts this dc voltage into ac voltage. The switching scheme used in inverter equalizes the power sharing among series connected modules, as shown in Fig. 2.11.

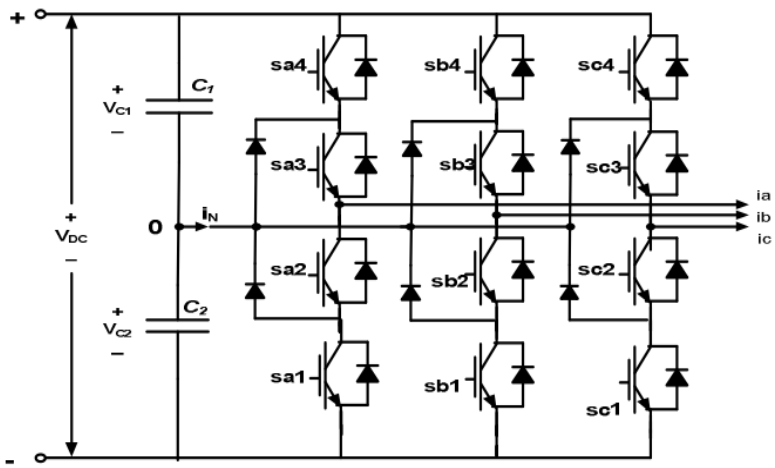


Figure 2.10: Neutral point clamped inverter [38].

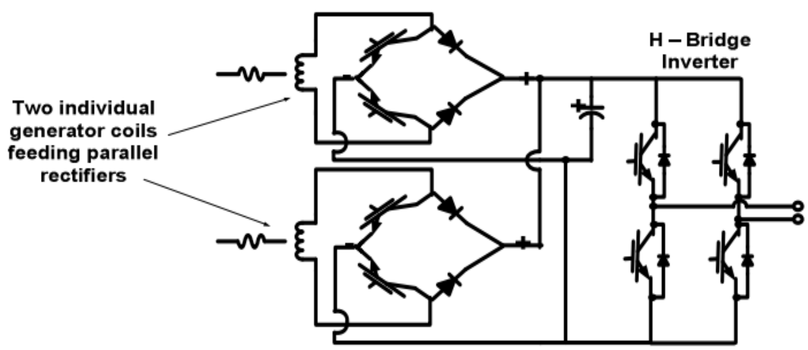


Figure 2.11: Two individual generator coils feeding two parallel rectifiers and H - Bridge module [38].

2.5.4 Matrix Converter

This topology has the advantage that generated voltage of PMSG is converted into desired ac output voltage without the need of any intermediate ac to dc conversion stage. In this type, the output of PMSG is converted by a reduced matrix converter, placed in the nacelle of each turbine, into a high frequency single phase ac voltage as shown in Fig. 2.12 [52]. A high frequency transformer of reduced weight and size is used for insulation purposes. HVDC transmission through under water cables in the sea, reduces cable losses and as it requires less number of conversion stages thus reduces the investment cost also.

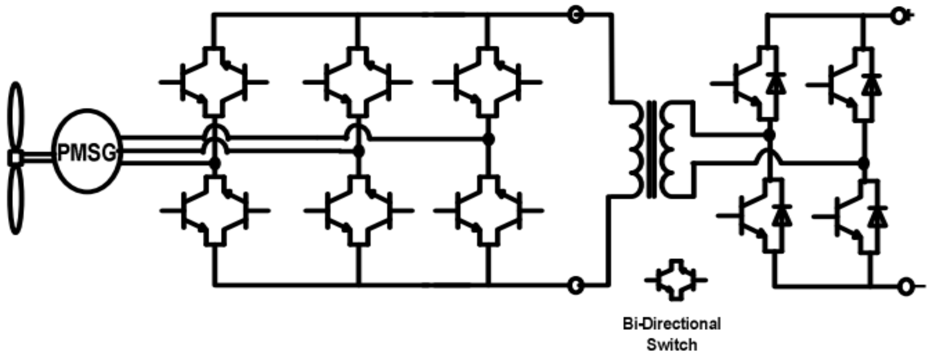


Figure 2.12: PMSG with reduced matrix converter [38].

2.5.5 Z-Source Inverter

In Fig. 2.16, PMSG based Z-source inverter is shown. Here the switching device count has been reduced by one in comparison to the conventional boost converter [63]. The reliability of the system is improved and total harmonic distortion (THD) is reduced by 40% in comparison to the conventional system. The generator output is feasible even during low wind speed condition as Z- source inverter boosts the voltage level.

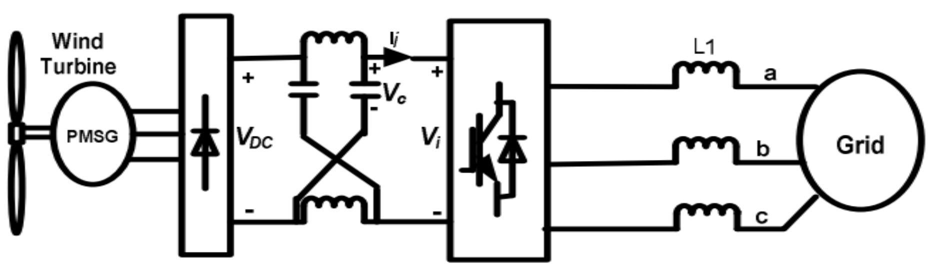


Figure 2.13: PMSG with uncontrolled rectifier and grid side Z- Source inverter [38].

2.6 DG and DN

For the sustainable growth of this universe, it is the high time to embrace with the renewable energy sources. To pull out effectively usable energy from renewables, many more modern technologies and devices are required. Among these devices, a popular technology used by various developed countries, is DG. At present the wind power is the most rapidly spreading sector and DG can work effectively with the wind power generation system. Wind power generation system is becoming more and more user friendly as it offers various shorts of benefits such as no fuel price volatility and so on. The wind based DG installation is taking place all over the globe now. With the increase in this utility with the distribution system, there are some technical concerns have aroused among the researchers. To set up the system of the wind connected DGs with the network, different types of switching power converters are used. These converters are the source of various issues regarding power quality. Various power quality problems arise with the installations of these converters and without these converters wind based DGs cannot effectively work. These DG converters cause harmonics and the harmonics generated in the system cross the limit of IEEE 1547 Standards. So, the wind based DG and its system design should be reconsider for making the wind based power generation more popular and industrialized.

DG units are recognized with various identities like “Decentralized Generation”, “Dispersed Generation”, and “Embedded Generation”. These DG units are small generating plants connected directly to the DN or on the customer site of the meter. DG has a positive meaning for developing the electric power system stability and also enhancing the power quality. DG capacity and voltage generally are lower and DG is employed in the electric power system at DN side. DG is a useful addition for a large power grid which is the main benefits of it. When the electric power system is failed, it is possible to deliver emergency power support by using this DG system. It will not only ensure the electricity supply of important users, but also will protect the system from any kind of accident. It upturns the power grid flexibility, reliability and improves power quality. In general, the remote area’s loads are too far away from the existing power system, so that it needs too much investment to build transmission and distribution systems and because of the harsh natural conditions, from the existing power system to user's transmission line is fully impossible to set up or after the completion, it will often fail. This DG system such as small hydropower, wind power, solar photovoltaic and biomass, is an effective method to resolve user’s electricity problem in remote areas.

This DG connection creates many problems in the electric power system .When a DG is connected to the system it increases the level of harmonics of the system because it consists various power electronics devices [54]. The harmonic distortions produced by the DG units is depended on various system parameters such as, the size of the dc link capacitor, the inductance of the inverter filter, the combination of local loads and non-linear loads and the line impedance of the power system.

The exact location of DG connection with DN is an important matter of concern and recently it catches the eyes of many researchers and many researches have been done in this issue. Optimal placing of DG in necessary because it is related to the power loss, voltage profile and so on [55], [56].

2.7 Power Quality Problems

To ensure the safety at both ends: customers and producers, the power quality is an important issue to look at. It has become more crucial as the use of various sensitive and critical equipment get increased this days. Expensive equipment are being used in precise manufacturing process, communication sectors, process industries, and even the home appliances are also very much sophisticated. So the clean and safe power must be ensured. The researches and industries are always looking towards developed technologies which can mitigate power quality problems.

The quality of power indicates the standards of current and voltage quality offered to the household consumers, to the industries and to the commercial supplies. Basically quality of power is the index of voltage and current conditions at the distribution ends. Many folds of PQ issues may cause in a system to deteriorate the current and voltage standards. Harmonics generation, voltage sag, swell, spikes and surges, voltage and current quality deviation are the major issues to deteriorate the power quality standards for any location in this globe. It is seen that harmonics effects are more acute in the case of wind energy penetration than the solar energy penetration to the feeder. When the centralized connection system is concerned, the current and voltage harmonic distortion is much less than the decentralized connection system.

A study conducted in the Berserker Street Feeder at Australia, has successfully prove that STATCOM reduces total voltage harmonic distortion at a good extent. In this study, an observation zone was developed with 910.418 kVA connected load and it is found that for this zone the current harmonic distortion decreases from 3.79% to 3.04%. The harmonic distortion get increased when renewable energy is integrated to the grid [57].

The intensity of saturation and the characteristics and amount of the harmonic source injection are influenced by the tap changer, capacitor, compensator, power factor and the level of generation of the wind turbine.

2.8 Harmonics

Harmonic is defined as the distortion of the waveform of current and voltage. The Fourier series of steady state waveform with equal positive and negative half-cycles can be represented according to equation [58] given below.

$$f(t) = \sum_{n=1}^{\infty} A_n \sin\left(n\,\pi \frac{t}{T}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

Where, *f(t)* = time domain function, *n* = harmonic number, A_n = Amplitude of the nth harmonic component, *T* = Length of one cycle in second

The total current and voltage harmonic distortions are mathematically expressed as [59],

$$I_{\mathrm{thd}} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\% = \frac{\sqrt{I_2^2 + I_3^2 + \ldots\ldots + I_n^2}}{I_1} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

$$V_{\mathrm{thd}} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\% = \frac{\sqrt{V_2^2 + V_3^2 + \ldots\ldots + V_n^2}}{V_1} \times 100\% \ldots\ldots\ldots \quad (2.3)$$

Here, V_{thd} = total voltage harmonic distortion, I_{thd} = total current harmonic distortion and they are calculated by RMS values (V_1, V_2, ….V_n) and (I_1, I_2,……. I_n).

Harmonics have become an extensively ameliorating problem, which is assumed to be much higher in the future as the non-linear power electronics devices are used all over the globe. It was estimated that at 2012, the 60% of the loads of USA would be nonlinear loads [60]. In recent years, the usage of switch mode power supplies has been a common tendency to feed power to the residential appliances. From the personal computers to the cellular phone battery chargers all of these common home appliances generate harmonics. In power equipment and components, harmonic causes various problems like it increases the skin effect which generates heat in the circuit. Moreover, the proximity effect of harmonics in conductors also generates heat. The eddy current losses in the transformers will be increased if the harmonics increased. If the harmonics increase, the capacitor will be overheated and dialectic stress will take place. Harmonics are also responsible for the failure of the circuit breakers. Not only this, due to harmonics the system resonance, a decrease in power factor, voltage distortion, interference with communication network, impact on energy metering problems occur. So as an overall result, the efficiency of the system decreases to a great extent and sometimes harmonics can collapse the whole system [61]. In early studties the harmonics generation were not precisely measured as there was no such technological advancement. But now the usage of sensitive technological devices and various communication devices has increased to a extreme level. So there is no other option than to deal with harmonics and for doing this accurately first and foremost critrion in to measure the harmonics accurately and precisely.

When wind based DG and DNs are concerned, the generation of harmonic gets increased due to the system itself. Even the nonlinaer loads connected to DNs, increase harmonics. Converters and technologies connected with the wind based DG rise the level of harmonics. So while talking about introducing wind based technologies to support DG connected with DN, it has become a high priority task to deal with harmonics generation.

2.9 Voltage Sag and Swell Issues

One of the widest spread power quality problems that affects the DN is voltage sag. Voltage sag and swell at industrial sector are common issues. This voltage sag interrupts manufacturing process, even, sometimes damages equipment. From the researches it is found that voltage sag comprises 92% of the power quality problems [62].

As the use of solid state switching devices, nonlinear loads, power electronically switched loads and electronic type loads are increasing, the power quality issues are also becoming a devastating problem of the power world. High power conductor switches are being used in devices. These conductors in the devices create distorted sinusoidal currents [63]. Voltage distortions and harmonics are created due to the electronics type loads. Power quality problems are now taking devastating condition and it causes tremendous problems for the system like, equipment malfunction, computer data loss, memory malfunction, damages of sensitive devices such as computer, programmable logic device controls (PLC), protection and relaying equipment [63].

Mainly due to faults and short circuits, lightening strokes and inrush currents this voltage sag takes place. Voltage swell is caused due to single line ground fault. Voltage swell can cause temporary voltage rise on the un-faulted phases [64].

DVR based on compensators are designed to protect sensitive equipment. The first DVR was used in North Caroline, USA at a rug manufacturer industry and second DVR was installed for large dairy food processing plant in Australia. This converter is connected with voltage source. This device usually provides protection to PLCs and adjustable speed drives (ASDs) from voltage sag and swell. This device monitors the load voltage waveform continuously and if needed it injects the desired voltage. For the achieving desired voltage waveform a pre-defined reference waveform is required and this reference waveform is designed according to the magnitude and phase angle of supply voltage. The device compares the voltage with the reference and in case of any abnormality, the device injects the missing voltage to support the system [65]. The DVR device provides some advantages to use it in the system. This device is sensitive to load level and independent to the system short circuit capacity and the installation position. The compensation capability of the DVRs can be improved. But energy storage is essential to supply power to improve the workability of the DVRs [66].

2.10 FACTS Devices

To mitigate power system oscillations the flexible alternating current transmission system (FACTS) devices can be used. The FACTS is a controller system of the power industry developed from the recent researches. It can control the network condition very rapidly and can improve the voltage stability as well as the steady state and transient state stabilities of a complex power system. This technology creates a room to work closely with existing network to its thermal loading capacity. As a result, the cost may be reduced as there is no need to construct new transmission lines. There different kinds of FACTS devices like static VAR compensator (SVC), thyristor controlled series capacitors (TCSC), static synchronous series compensator (SSSC), STATCOM and so on [67], [68].

2.11 STATCOM

The STATCOM is a shunt device. However, this STATCOM does not have any capacitor or reactor banks. SVCs can generate reactive power but the STATCOM can not. So to amplify the possibilities of STATCOM, it can be employed with capacitors. The capacitors maintain constant voltage for the voltage source converter. Common unit of STATCOM topology is a six pulse unit. 48 pulse topology can even be created by the amalgamation of 8 six-pulse converters. In multi-pulse topology, the measured displacement angle of two consecutive six-pulse converter is $2\pi/6m$, Where, m = Number of total six pulse converter. Magnetic circuits used in six-pulse converter to control the phase adjustments. The angle of the STATCOM voltage varies with the ac voltage. STATCOM inject reactive and capacitive current at the AC system bus by controlling this angle of STATCOM voltage.

Earlier used traditional synchronous compensators, like SVC was too large in size, had lower speed and lower range of operational range. STATCOM, on the other hand, is high performing device successfully compensating the reactive power, suppressing the harmonic current and providing voltage support for transmission system. All these characteristics make it a famous and eye-catching technology among the domestic and foreign researchers and scientists as well as the academics.

The workability of STATCOM is well appreciated as quickly and accurately it can absorb or inject reactive power to stabilize voltage excursions theoretically and practically. It can successfully maintain a pre-set voltage magnitude. It improves the transient stability and sub synchronous oscillation damping. In comparison to standalone STATCOM, the combined STATCOM with energy storage system provides better dynamic performance. STATCOM/BESS increases flexibility and control transmission and distribution system as STATCOM/BESS ensures rapid and independent active and reactive power absorption and injection. The conventional STATCOM operates in two modes, namely, inductive (lagging) and capacitive (leading) [69]. The traditional STATCOM can support the system controlled output voltage and phase angle. As the traditional STATCOM does not have significant active power capability, the output voltage and phase angle cannot be independently adjusted in the steady state operation mode. So the traditional STATCOM cannot deal with active and reactive power quality issues simultaneously.

For controlling STATCOM, various methods are introduced. Many researchers used Bang-Bang controller. It is used to obtain STATCOM current which is to be introduced into the grid. The controller uses a hysteresis current controlled technique. Using such a technique, the controller keeps the control system variable between the boundaries of hysteresis area and gives correct switching signals for STATCOM operation. The current controller block receives reference current and actual current as inputs and are subtracted so as to activate the operation of the STATCOM in current control mode. From a research it was find that THD reduced from 5.15 % to 1.92% when STATCOM is applied in the system [70]. The disadvantage of this method that the controller circuit is more complex.

Another STATCOM control scheme is fuzzy logic controller. The inputs of the controller are change in grid voltage (ΔV) and change in grid current (ΔI) and they represented as membership functions of the controller .The output gives switching signals for IGBTs of STATCOM (ΔU). The THD analysis revealed that the fuzzy logic controller is good compared to bang-bang controller. From a study it was proved that the fuzzy logic controller is simpler and has faster response than BANG-BANG controller. Without using STATCOM the source current THD is 8.50%, and by using BANG-BANG current controller with STATCOM the THD in the source current reduced to 1.93% whereas by using Fuzzy logic controller with STATCOM the THD is reduced to 0.43% [71].

If a battery source is connected with the STATCOM system, it performs better and more effectively. Battery profile effectively control charging and discharging mechanism. Battery based STATCOM has better dynamic performances. It can push and pull independent active and reactive power and thus ensures flexibility and superior control over distribution and transmission network. Not only this, operation freedom is also ensured if battery is installed.

Conventional STATCOM operates in two modes, namely, Inductive (Lagging) and Capacitive. This type of STATCOM does not provide active power to the system rather it takes active power from the system to compensate its losses due to operation. On the other hand, STACOM/BESS has wide range of working capabilities. It has four modes of operations [72], such as: inductive with dc charge, inductive with dc discharge, capacitive with dc charge, capacitive with dc discharge. In this thesis, STATCOM/BESS performs as a filter. Generally, a dc Link capacitor is used in the STATCOM. But in this research, a battery source is used with a dc link capacitor. STATCOM/BESS injects same and opposite amount of harmonics current in the system to eliminate harmonics. Battery will be charged when the load is lower than generation and when the load is higher than generation the battery will provide power to the system. Thus, the harmonics of the system is eliminated through the modified STATCOM.

2.12 Harmonics Reduction Techniques

Harmonics generated in the grid network is a very critical problem. And with advancement of the technological world the harmonics generation is becoming more and more acute. Academics and researches have proposed various models and systems to attenuate harmonics from the system. Still no perfect solution is achieved. But matter of hope is this research has attracted the attention of various scholars, organizations and countries.

Grid faces power quality problems like harmonics for using inverters, which releases high frequency pulse with modulation and this can be reduced by using filters like L, LC, LCL filters. But L filters need bulky components to provide sufficient attenuation and also need a high carrier frequency to remove harmonics. In the same way, LC filters cannot be used with the grid connected system since for resonance frequency, it is dependent on the grid frequency. When the inductance value is small in LCL filter, it can attenuate current ripple perfectly. Due to unaccepted resonance effect, it faces stability problems. So the LCL filters can be used with suitable performance when the resonance condition prevails.

Many papers have already proved that LC filters are somehow successful to eliminate harmonics to some extent only. In a study, a 1 hp 50 Hz five phase induction motor drive (FPIMD) was used as a load to measure the harmonic effect in the system and to remove this harmonic from the system, LC filter was incorporated, where the LC filter was designed to be capacitive in action and its fundamental frequency of impedance was at a desired rate. The specification of the LC filter was: C= 1000 μF and L= 42 mH and the resonant frequency = 24 Hz. In FPIMD, with LC filter the THD is reduced from 42.2% to 21.57% [59].

A common source of harmonic is six pulse bridge rectifiers and various studies are done form minimizing this harmonic effect. A research represents a method where a third harmonic current is injected in the common point of transformer secondary winding. For this a third order harmonic voltage is used and placed between output of the bridge and common point of the transformer secondary. Two 150 Hz tuned passive LC filters generate accurate harmonic currents of proper phase and magnitude. Usually the primary transformer winding arrangements are delta and star, on the other hand, secondary winding arrangement must be star that provides the access to the common point of the transformer secondary. From the laboratory tests and simulation results, it is confirmed that the harmonic current distortion of the supply effectively reduced from 27% to 4.5% [73].

Fluorescent lamps may generate harmonic current especially in commercial building. This harmonic current causes overloading of switch boards and neutral conductors. The solution of this problem can be achieved through splitting the distribution transformer into two transformers through secondary winding. These winding should be out of phase and the neutral conductor is shared by the two transformers. But the study here, provide solution by adding a passive LC filters in neutral conductors. This filter is special designed and has a characteristics which allows to flow the first harmonic component but impede higher harmonic currents in the neutral conductor. This proposed model is effective to reduce harmonic current in the conductor and phase supply lines. The laboratory tests also testify the statement [73].

Compact fluorescent lamp (CFL) is widely used this days and this CFL causes harmonics in the system. Loads with diode bridge rectifier influence harmonics generation. But from analytical studies, it is seen that the size of the dc link capacitor is the main deciding factor of harmonics level and intensity. The less the size of the capacitor, the less the current THD [74]. But the main problem is, if the size of the capacitor is too low, the dc bus voltage ripple increases and light flicker takes place. So the appropriate size of the capacitor is very much essential to have proper light intensity and safe and sound electric connection. The studies has stated that in large usage the capacitor, size helps to reduce harmonics. So manufacturers now applies different sizes of capacitors with same wattage to go for the cancelation of harmonics in CFL to ensure safety and effectively.

From the above studies, it is clear that every single non-linear load has its own characteristics and harmonic generation level and reduction of this harmonics, specific technique can be applied but in the DN various kind of non-linear loads are connected. So, it will be very costly and complex to apply different technologies for removing the harmonic effects of different loads.

Shuffled frog leaping algorithm (SFLA) is a method to deal with harmonics in the inverters [75]. It can calculate switching angle for the eleven level inverter. From this method, optimum solution of selective harmonic elimination problem can be achieved, especially in case of low modulation indices. Main advantages of this method are easy implementation and fewer parameters that are considered. This method is an offline method, which needs continuous supervision and separate lookup table and this is the main disadvantages of it.

To reduce harmonic distortions in power systems, cascaded active power filter were used [76]. Two active power filters were connected in cascade with different operating frequencies and different power ratings. In power systems, the amplitude of harmonics and harmonic orders are inversely proportional to each other. Similarly, switching frequency of devices is inversely proportional to the power capacity. So, one of the active power filters with low power rating and high switching frequency compensates for higher order harmonics and the other active filter with high power rating and low switching frequency reduces the lower order harmonics. Thus the cascaded active filter reduces higher harmonics as well as the lower order harmonics effectively [76]. The demerits of the active harmonic elimination is that to reduce higher order, high Switching frequency is needed and also to generate firing signals for the switching control procedures becomes complex.

The hybrid passive filter (HPF) topology is proposed to eliminate the voltage and current harmonics as well as the reactive power of large scale nonlinear loads. A series of passive filter and a variable impedance shunt passive filter are used to construct HPF. The shunt passive filters are based on thyristor controlled reactors. The generated series passive filter inductance rating is minimized through the concept of mutual inductance. The advantages of this method are fast dynamic response, reduction in size of the shunt passive filter capacitor significantly, no series and parallel resonance problem. This technology can minimizes current source type nonlinear load's THD up to 1.2% from 26% for delta connection and voltage source nonlinear load type nonlinear load's THD up to 1.1% from 47.3% [77]. This research does not explain how this technique can deal with power quality issues like voltage sag and swell.

Distributed static compensator (DSTATCOM) is a common technique to get rid of harmonics. New approach of DSTATCOM assembled with a supercapacitor is designed to have better performance from DSTATCOM. The architecture of the DSTATCOM is modified with a voltage source converter (VSC) based DSTATCOM, a dc-dc bidirectional chopper and the supercapacitor. A dc-dc bidirectional chopper decides the charging and discharging of the model and the supercapacitor tries to maintain the voltage across the dc bus capacitor. Switching signals for IGBTs of VSC are produced by applying instantaneous symmetrical component theory control techniques. From theoretical approaches, it is found that the source current THD can be reduced using DSTATCOM from 20.66% to 2.76%, but applying super capacitor based DSTATCOM, it can be reduced up to 2.02% [78]. However, this approach has done a significant reduction in harmonics, till this does not deal with voltage sag and swell. It uses supercapacitor which increases the cost of the total technique.

2.13 Summary

The literature review part has considered diversified and various research articles, journals, papers of renowned academics. It has focused on the utilization of renewable source based power generation, emphasizing on wind based power generation system and technology and more importantly the power quality issues and techniques of mitigation.

CHAPTER III

Model Design

3.1 Introduction

DG based on wind turbine is one of the most growing, effective and potential technologies which has been scattered over the globe. The model is developed where a PMSG based wind turbine is connected to the DN through an AC/DC/AC converter and a STATCOM/BESS is connected parallel to the system to mitigate the power quality and power stability problems as shown in Fig. 3.1. The control mechanism of the generator's converter is based on the straight line theory and the PWM technique is used for designing the voltage source converter of the STACOM/BESS. A proper integration between these control mechanisms creates a stable system. The description of the model is given with illustration of workability and efficiencies of its components. The model is designed and analyzed under PSCAD/EMTDC environment. The designed model has various parameters, under which the model has operated. Using different standardized parameters, it has been tried to create the actual environment.

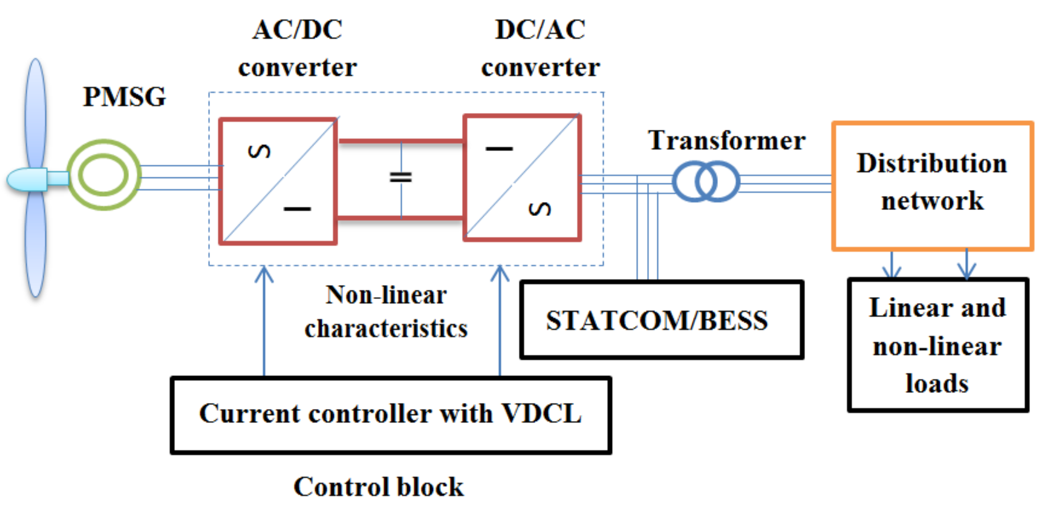


Figure 3.1: Proposed model of wind power system based DG.

3.2 Methodology

Every single piece of work needs to follow some steps for completing the total work. In this research work these steps to be followed to design and simulate a total system are given below:

• Step 1: Design a PMSG based wind system which will able to provide the maximum amount of power.

• Step 2: Design an AC/DC/AC converter with voltage dependent current limiter based on straight line method.

• Step 3: Establish distribution grid connection with loads and connect the DG and run the system.

• Step 4: Design the STATCOM/BESS with PWM control mechanism and connect it to the system and note data and take the spectrum.

• Step 5: Ensure the stability of power system as well as the elimination of harmonics and voltage sag and swell is done properly.

The flow chart of the total system is given below. In this Fig. 3.2, dc bus voltage (V_d), volts for applying limit (V_{on}) and volts for removing limit (V_{off}) are the parameters of AC/DC/AC converter. The total research is done by this methodology.

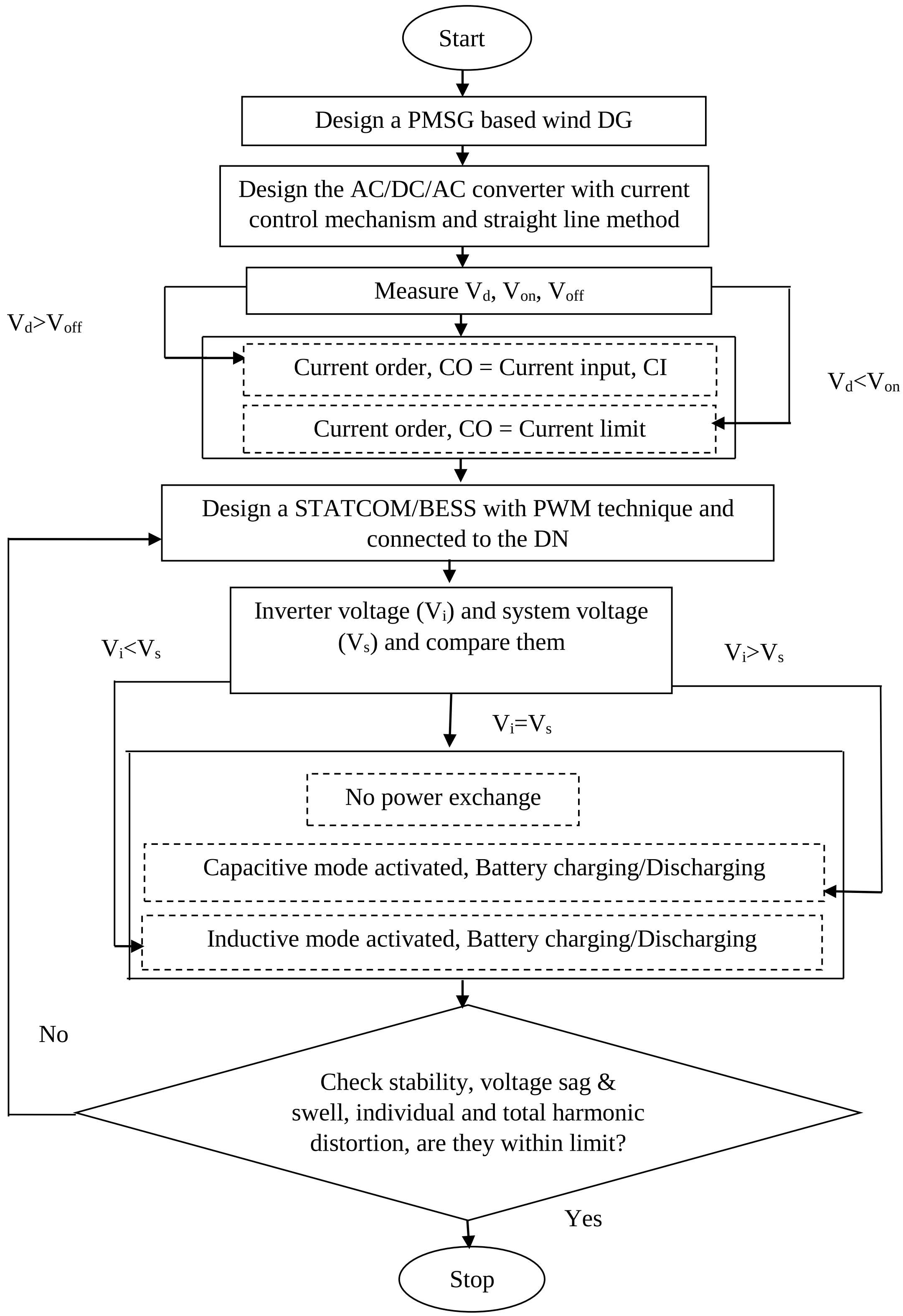


Figure 3.2: Flowchart of the proposed wind based system design methodology

3.3 Model of Wind System

In this model, the power generation from wind turbine using PMSG is portrayed as shown in Fig.3.3. The model is designed with various components. The description of this model is given below:

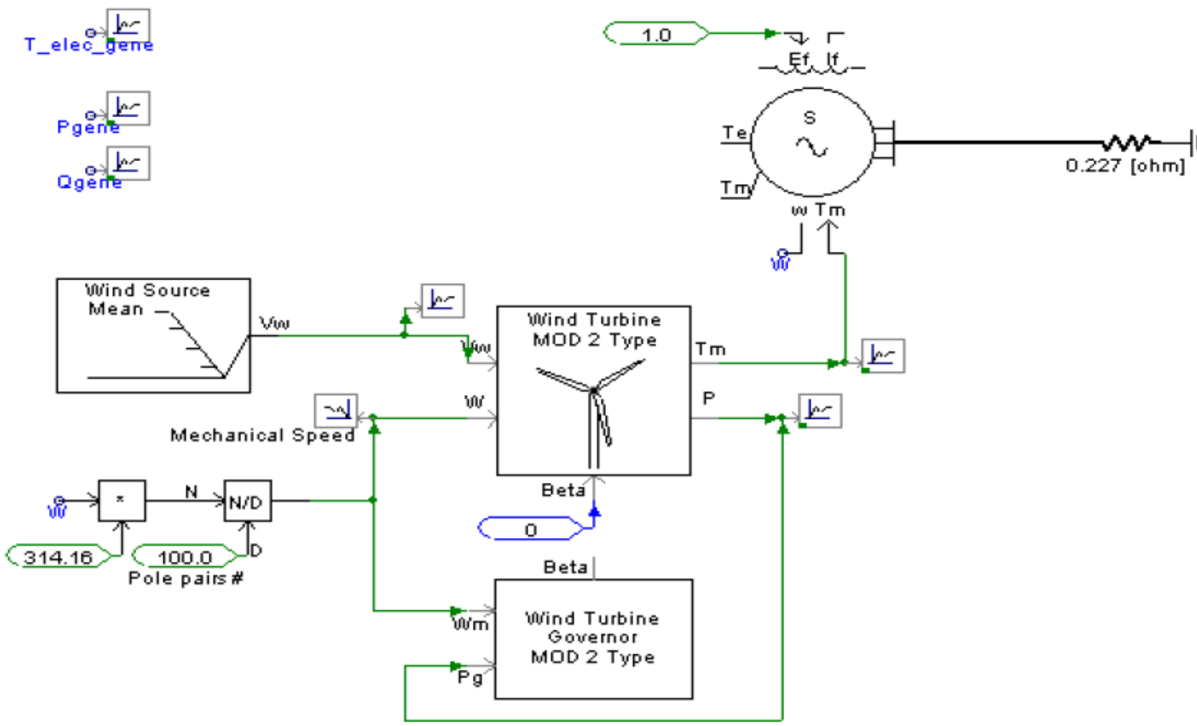


Figure 3.3: Wind model with PMSG.

Initially, the wind velocity and its effects have taken into account to create an exact situation of wind flowing. From statistics, it is found that the mean wind velocity is 13 m/s and in this research design, this value is used. The wind speed is an important issue because generation of power is depend on the wind speed. The blades are designed to operate within 4 to 25 m/s. The lower limit 4 m/s is termed as cut-in speed. Above the speed 4 m/s, the mechanical brakes go to the working region and the turbine will start. The higher limit of speed is 25 m/s and higher than this speed the rotation of the turbine is mechanically stopped in order to prevent the damage of the blades.

The model is incorporated with the wind turbine component. The wind turbine has three input parameters. These components primarily work in the predefine wind velocity (V_w) conditions. To set the environment effectively, the wind blade's mechanical rotation (W) must be considered. Beta (β) is the pitch angle of the turbine blades and is entered in degrees. T_m and P are the output torque and power respectively, based on the machine rating. The component is designed under MOD 2 type configuration. In this configuration, there are three blades in the system. To operate the wind turbine, a MOD 2 type governor is installed with it. The governor provides the beta angle and needs to study in this case. Usually the mechanical rotation speed (W_m) and power (P_g) of the wind turbine work as an input.

For calculating the turbine rated power the following mathematical approaches are taken into consideration and the notations that used in this mathematical model are given below:

E = Kinetic energy (J)
m =Mass (kg)
W_s = Wind speed (m/s)
P = Power (W)
$\frac{dm}{dt}$ = Mass flow rate (kg/s)
$\frac{dE}{dt}$ = Energy flow rate (J/s)

ρ = Density (kg/m^3)
A= Swept area (m^2)
C_p= Power coefficient
r = Radius (m)
t = Time (s)
x = Distance (m)

Under constant acceleration, the kinetic energy "E" is equal to the work-done "w". Here, an object has mass "m" and velocity "W_s", is displaced and covered a distance "s" with a force "F", that is

$$E= W= F\,s \quad (3.1)$$

According to Newton's Law, we know, $F = m\,a$

Thus, $E = m\,a\,s$

According to the third equation of motion, $W_s{}^2 = u^2+2as$

Now, $$a= \frac{(Ws^2-u^2)}{2s} \quad (3.2)$$

Since the initial velocity of the object is zero, i.e. u = 0, so, we get,

$$a= \frac{Ws^2}{2s}$$

Substituting it in equation (1) we get that, the kinetic energy of a mass is:

$$E=\frac{1}{2}\, m\, W_s^{\,2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

The power in the wind is given by the rate of change in energy:

$$P = \frac{dE}{dt} = \frac{1}{2}\, W_s^{\,2}\, \frac{dm}{dt}$$

Hence, mass flow rate is given by $\frac{dm}{dt} = \rho A \frac{dx}{dt}$

And the rate of change of distance is given by

$$\frac{dx}{dt} = W_s$$

Therefore, from the equation (3) the power can be defined as,

$$P = \frac{1}{2}\, \rho A\, W_s^{\,3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.4)$$

The density function, $\rho = 1.2925 \frac{(P_r - VP)}{760} \frac{273}{\mathrm{T}}$ kg/m^3

Here, P_r= Pressure in mm of Hg, VP= Vapor pressure of water vapor, T= Temperature in degree Kelvin.

The vapor pressure can be found if the dew point is known. But the vapor pressure corrections affect the density by less than 1%. Hence it is usually dropped from the calculation.

The power in the wind is converted to mechanical power with efficiency (Coefficient of performance) C_p and thus the equation of power at the output becomes,

$$P = \frac{1}{2}\, C_p\, \rho A\, W_s^{\,3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

Here, $C_p = 0.5\, (\gamma - 0.022\beta^2 - 5.6)\, e^{-0.17\gamma}$ .... (3.6)

Where, $\gamma = W_s * 2.237$ / Hub speed... (3.7)

Hub Speed at 50 Hz = $2 * \pi * f$ / 100 = 3.1416 rad/sec

Now, γ = 13 * 2.237 / 3.1416 = 9.25

Considering β is equal to zero, $C_p = 0.5\, (9.25 - 0.022 * 0^2 - 5.6)\, e^{-0.17 * 9.25} = 0.4$

In this model, 3 MVA generator and 3 MW turbine is taken. The radius and surface area of the rotor should be calculated precisely to develop an efficient model. The radius and area of the rotor are calculated using the following formula

$$P = \frac{1}{2} C_p \, \rho A \, W_s^{\,3}$$

As the generated power is 3 MVA so the calculated Area, A = 6714 m^2

And the radius of the rotor, r = 46.2 m [$A = \pi r^2$]

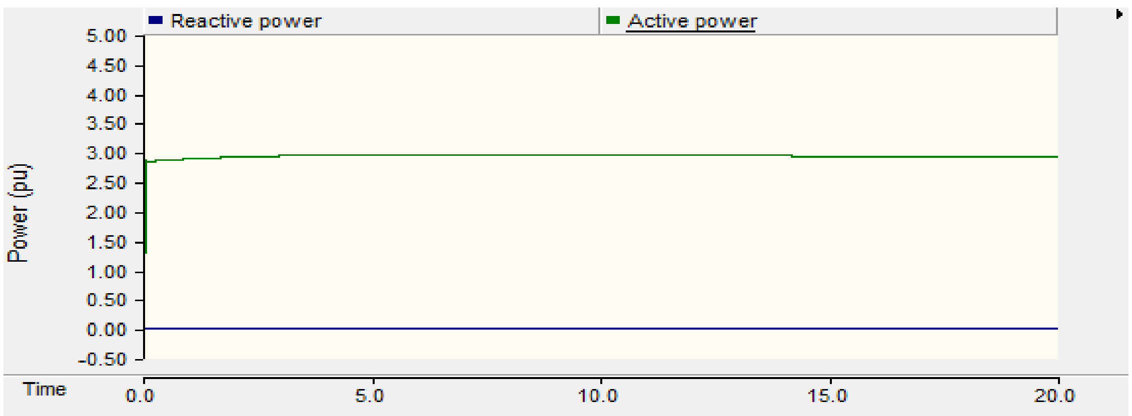


Figure 3.4: Generator reactive power and active.

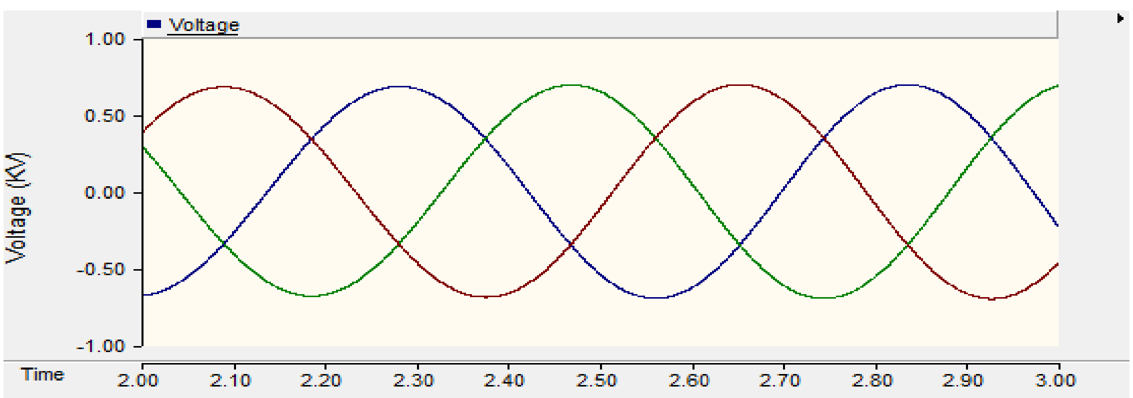


Figure 3.5: Rated voltage of generator.

The wind turbine is connected with a PMSG. The speed of the PMSG is controlled directly by inputting a positive value into the w input of the generator, or a mechanical torque may be applied to the Tm input. As a PMSG is taken to the consideration, the excitation part is omitted. The rated power of PMSG is 3 MVA, the rated voltage is 0.69 kV and the rated current is 1450 A. The active power from this wind system is almost 3 MW whereas the reactive power is almost zero and this proves its efficiency of this model as shown in Fig. 3.4. The generator power is matched with the turbine rated power. Figure 3.5 and Figure 3.6 portray the rated voltage and current of the generator. From these Figures, it is clear that there is no harmonic pollution and it is purely sinusoidal.

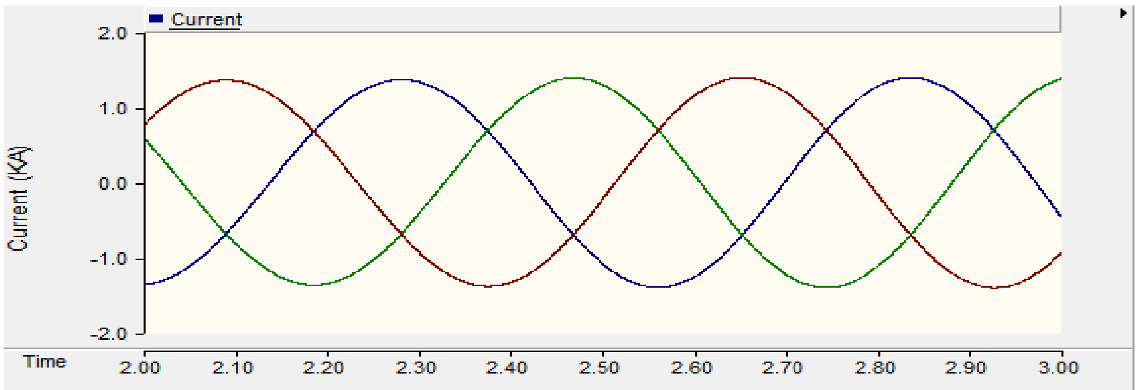


Figure 3.6: Rated current of generator.

The C_p is influenced by β. There are two approaches define the β component, as dynamic pitch control and passive pitch control

3.3.1 Dynamic Pitch Control

In this case, the wind turbine governor regulates β (Fig. 3.7). A hard limiter is set with cut-in and cut-off values to control and design wind turbine similar to the actual situation. As per the wind speed operation, the upper limit and lower limit here is 4 to 25 m/s.

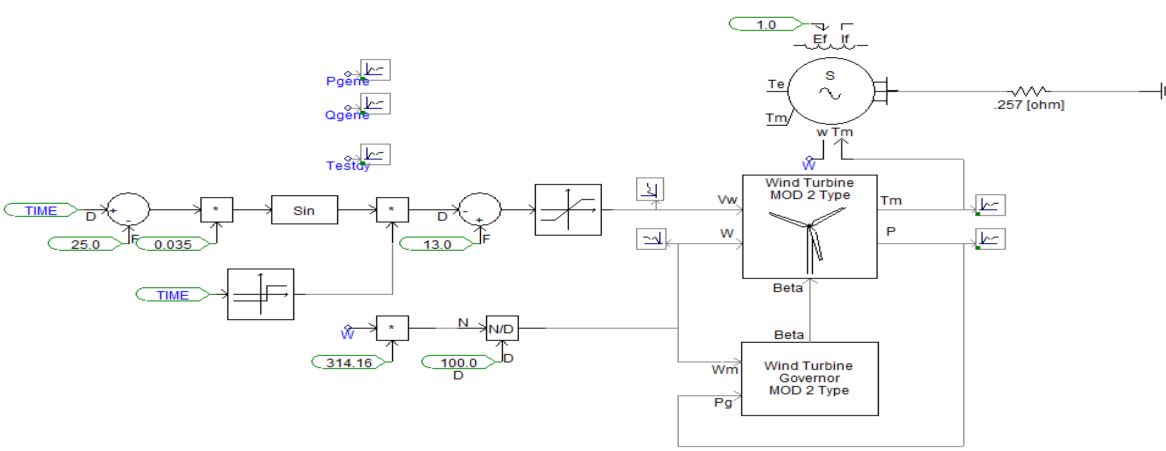


Figure 3.7: Wind model with dynamic pitch control.

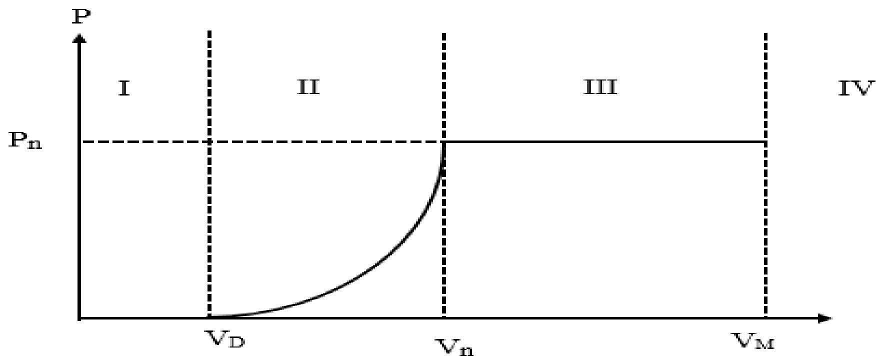


Figure 3.8: P (V) characteristics in dynamic pitch control

In dynamic pitch control, the blades can rotate according to its longitudinal plane. The power that is produce in the dynamic pitch control is different for different regions as shown Fig. 3.8 and Table 3.1.

Table 3.1: Working reason of P (V) characteristics in dynamic pitch control

Zone 1	$V_w < V_{\text{cut-in}}$	P= 0, the turbine does not move
Zone 2	$P < P_{\text{rated}}$	P = f (v) with β= 0
Zone 3	$P = P_{\text{rated}}$ with $\beta \neq 0$	P is kept at P_{rated} through the dynamic pitch control
Zone 4	$V_w > V_{\text{cut-out}}$	P=0, the wind turbine is stopped.

3.3.2 Passive Pitch Control

In this control mechanism the blade is designed to capture the maximum amount of power until a fixed limit. If the limit is crossed, the power is set to a constant value. The main difference between dynamic and passive control method that, in passive control, the β is not governed by the wind governed rather it has a fixed value. In the model, the rated speed is taken same as the mean value. Thus, in this simulation, pitch angle is set to zero for achieving the rated power in the speed of 13 m/s. In this case, the nominal value is defined as the hard limit, which is 13 m/s above this value, turbulence is stopped to increase. In passive pitch control method, β is taken as zero for getting the maximum amount of power because if the value of β is increased then the power will be decreased. When the β value is taken as 15 then the power is decreased from its rated value as shown in Fig. 3.9.The pitch regulation technique keeps the rated value at a desired point. But the dynamic pitch control technique provides more power to the grid as it can work under different wind speed conditions. The dynamic pitch control is an expensive technology and it can provide more energy than the passive pitch regulation. For economic reason passive pitch controller is more popular.

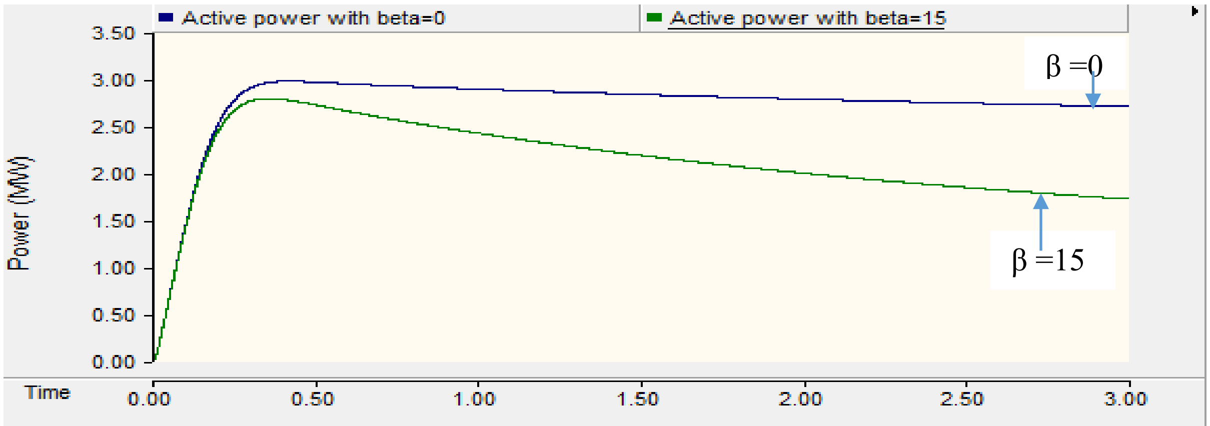


Figure 3.9: Active power in passive pitch control method with β =0 and β =15.

3.4 Proposed AC/DC/AC Converter Model

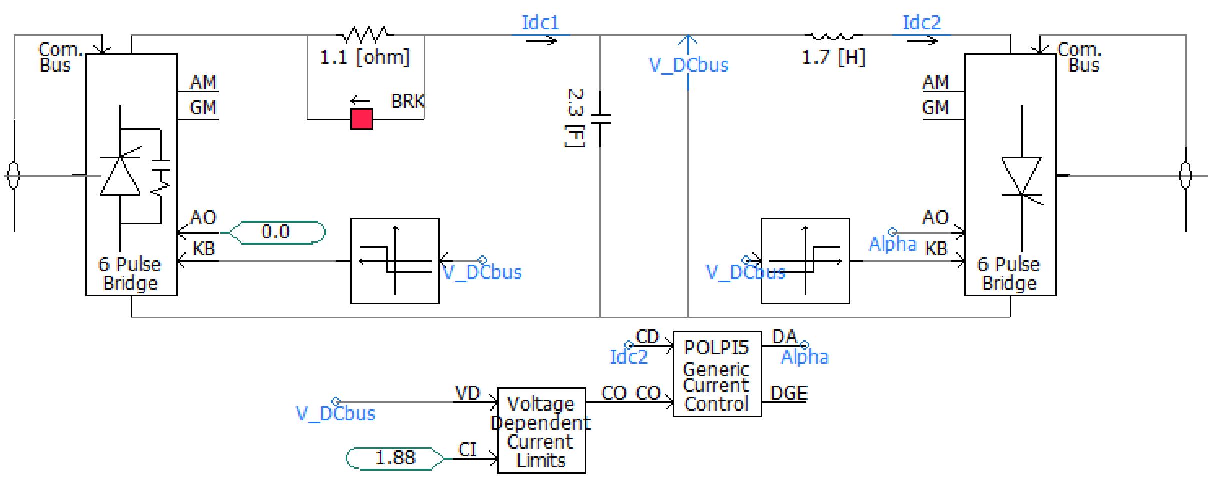


Figure 3.10: Model of AC/ DC/AC converter.

The AC/DC/AC converter is used to connect the output of the synchronous generator with the grid as grid needs power with stable voltage and frequency. This device is used to pull out the maximum amount of power from the generator and stabilize the voltage and frequency before feeding to the grid. However, it is a non-linear load in nature. Non-linear loads generate harmonics or distortion in the sinusoidal wave form of the current. Second thought may come of avoiding the AC/DC/AC converter from the system. But without this device, it is difficult to push the power into the grid due to voltage and frequency issues. So, this device must be implemented in the system. The AC/DC/AC converter has three important components (Fig. 3.10), such as diode rectifier, dc Bus with a storage capacitance voltage, 6 pulse bridge thyristor inverter.

3.4.1 Diode Rectifier

A three phase diode rectifier is designed and input signals are ComBus, KB, AO whereas AM and GM are the output signals. The voltage reference for starting conduction represented by ComBus, blocking/deblocking signals is presented by KB and AO presents the firing angle from the reference and the extinction angle which is an output signal measurement is represented by GM. The 6-pulse bridge is used as a diode bridge and at this time AO consider as 0.When the speed of the generator increases at this time the voltage also increases. However, it is not possible to control the generator's speed. For protecting the dc bus from over voltage condition, 10 % secure margin is taken. By using a single input level comparator, it is possible to block the rectifier in the situation of over voltage.

So the rated dc bus voltage is, $V\_\text{DCbus} = (3*\text{Vn}*\sqrt{6})$ …………………………… (3.8)

$$= 3*690*\sqrt{6} = 1600\text{V}$$

Then, the maximum voltage for secure margin = 1.1*1600 = 1760 V

3.4.2 DC Bus with a Storage Capacitance Voltage

For designing this part, a storage capacitor, a resistor and a breaker are used. The rating of the capacitor and resistor must be calculated.

In the capacitor the energy stored must be, $W = P*1\text{s} = 3\text{MJ}$.

As we know, energy, $W = 0.5*C*V\_\text{DCbus}^2$………..……………………… (3.9)

So the capacitor value, $C = 2*W/V\_\text{DCbus}^2 = 2*3/1600^2 = 2.3$ f

The capacitor can be modelled as a short-circuit when it is discharged; thus a resistor must be included in order to limit the current peak to its rated value when the capacitor is at low charge.

The rating of the resister, $R = V\_\text{DCbus} / In = 1600 / 1450 = 1.1\ \Omega$

In this circuit, a single phase breaker is incorporated to stunt the resistor. This is a first order system so that the load constant, $T_r = 3* t = 3*R*C$ …………………………………… (3.10)

$= 3*1.1*2.3 = 7.5$ s

For limiting the joule losses the resistor must be shunted after 7.5s (Fig. 3.16). At t=7.5s, the resistance is shunted, the capacitor is charged, the over-voltage regulation limits the bus voltage at 1760 V and Idc goes to 0 so that the delivered output power of the generator becomes zero and then new steady state condition starts.

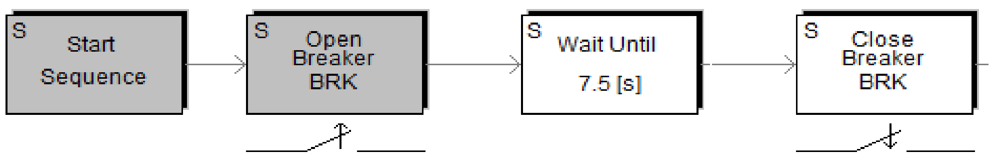


Figure 3.11: Breaker operation sequence.

3.4.3 Six Pulse Bridge Thyristor Inverter

The modeled inverter is a current inverter with thyristors. Basically, the current flows in one direction whereas the flow of voltage is bi-directional. An inductor is added in order to model a current source at the input of the inverter. The rating of the inductor has to calculate very precisely.

We know, energy stored in inductor, $W= 0.5*L*I_{dc}^2$ …………………………………… (3.11)

Here, $I_{dc} = P_{dc}/V_{dv}$ ……………………………………… (3.12)

$= 3/1600= 1875$ A

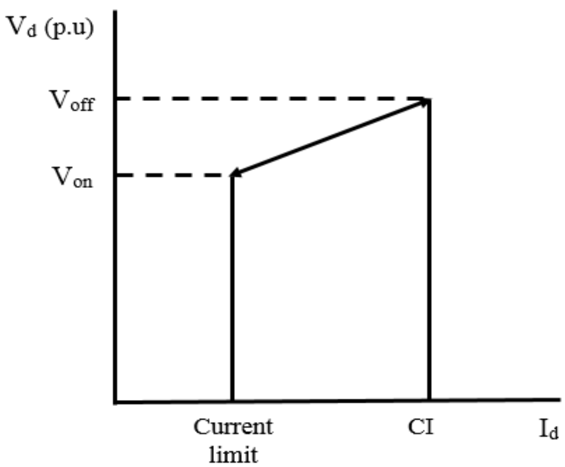
So, value of inductor, $L = 2*3000000/1875 = 1.7$ H

This inverter have two more function one is, the dc bus voltage collapse limitation in case of fault on the distribution system and another one is, the dc bus voltage control. The secure margin is about 10% for overvoltage limitation. We will stop the rectifier in case of low-voltage to secure the bus.

So, the low voltage limitation = 0.9*1600 = 1400 V

3.4.4 Proposed Control Mechanism of AC/DC/AC Converter

The voltage dependent current limiter (VDCL) is used to control the voltage collapse mechanism. If any short circuit occurs in the ac system, then the voltage will be collapsed and then VDCL will recognize it and take the current order to a certain level. The VDCL only permits the flow of current within a predetermined value. V_{on} is the lower limit and V_{off} is the higher limit voltage and these parameters must be in the same polarity as the measured voltage and V_{off} always greater than V_{on}. The system is designed through the straight line method as shown in Fig. 3.12. For limiting the system's current, two conditions are implemented so that the over and under current situations can be avoided which not only protect the system but also reduce the generation rate of harmonics. In this system, input parameters are the measured dc bus voltage (V_d) and reference current (CI) whereas the output parameter is the current order (CO).



- When, $V_d > V_{off}$ then, CO=CI; which is the current for the rated power.
- When $V_d < V_{on}$ then, CO=current limit; which is the minimum current in the inverter.

Figure 3.12: Straight line method.

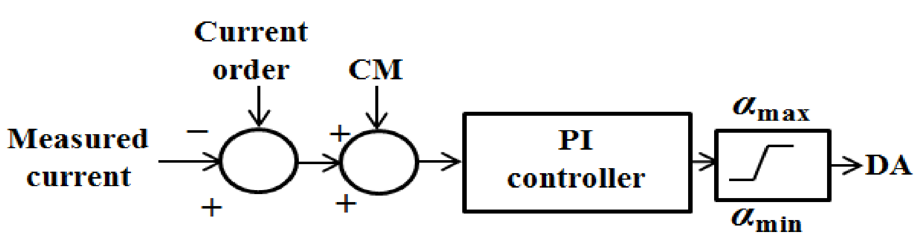


Figure 3.13: Current controller model of AC/DC/AC converter.

The current controller is used in this system to act on the error between current order and measured dc current as shown in Fig. 3.13. This controller provides a desired alpha order (DA) to generate firing angle for each series group of valves. The current margin (CM) generally has a fixed value and in normal operating condition, it is zero. If under normal operating condition the converter is not controlling current, then it is forced into establishing dc voltage by setting CM positive for an inverter or negative for a rectifier. This force takes the desired firing angle at an inverter to the maximum level of alpha (α_{max}). At the rectifier, a negative CM forces the firing angle to alpha minimum limit (α_{min}).

The current input is the current for the rated power, *I*dc = *P*dc/*V*_DCbus = 3000000/1600 =1880 A = 1.88 kA. The fluctuation of the dc bus voltage must remain between, *V*dv-5% < *V*_Dcbus < *V*dv+5% ; 1520 V < *V*_Dcbus < 1680 V. Below 1.52 kV the current will be set to 0.06 kA (minimum current in the inverter) and above 1.68 kV the current will set to 1.88 kA for avoiding the collapse of the system. Current controller integral gain (GI) lies between 3<GI<6 and current controller proportional gain (GP) lies between 0.01<GP< 0.02.

3.5 Proposed Model of STATCOM/BESS

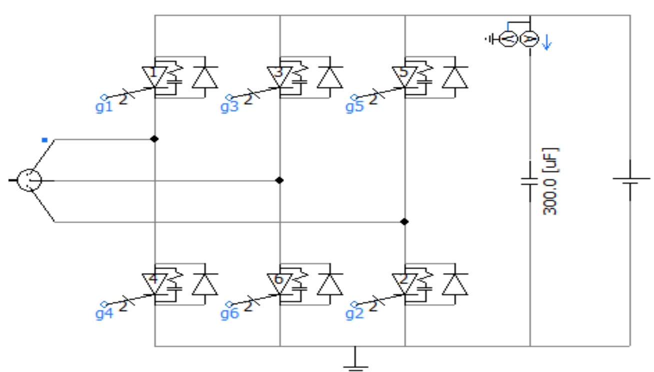
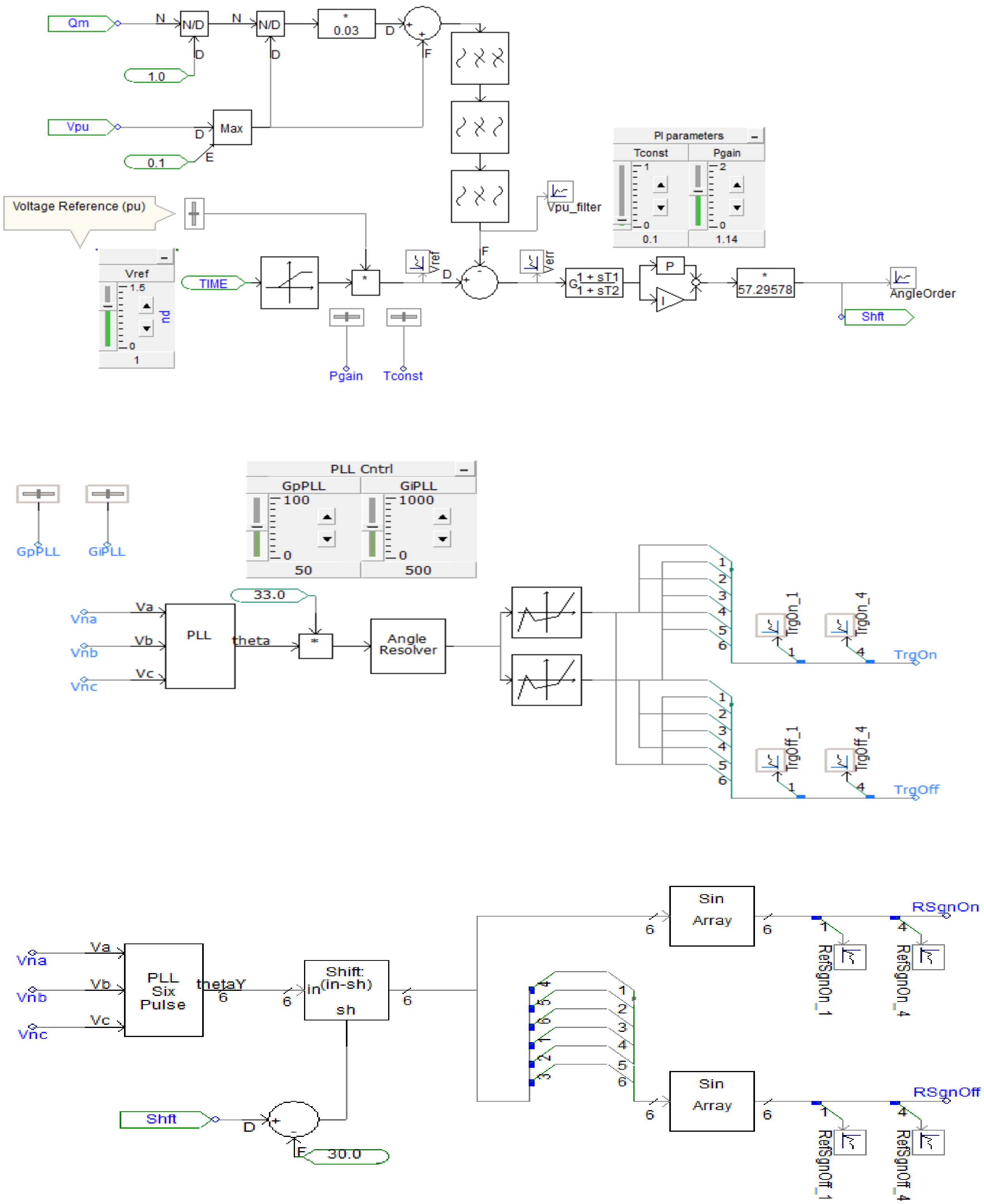


Figure 3.14: Model of STATCOM/BESS.

STATCOM/BESS with voltage-bridge circuit has higher popularity and the model of STATCOM/BESS used in this research is also designed with voltage bridge circuit as shown in Fig. 3.14. The voltage bridge based STATCOM/BESS is designed with the components like dc side capacitor, voltage source converter (VSC), high power electronic switching device i.e. GTO, pulse width modulation technology (PWM). The dc side capacitor provides support to voltage. The rating of the dc link capacitor is 300 μF. The PWM technology controls the power electronic switch and helps to generate pure sinusoidal waveform (Fig. 3.15).



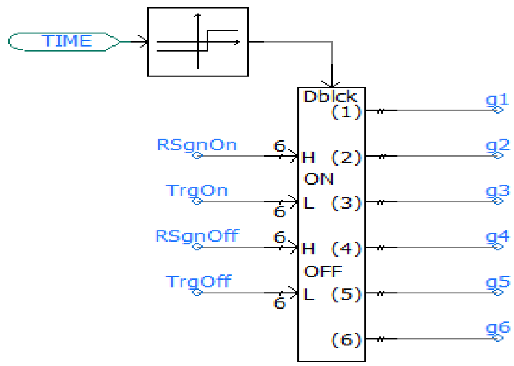


Figure 3.15: Control mechanism of STATCOM/BESS.

3.5.1 Proposed Control Mechanism of STATCOM/BESS

The control mechanism of the proposed STATCOM/BESS is based on the PWM technique where two phase lock loops (PLLs) are designed for maintaining the system operation smooth.

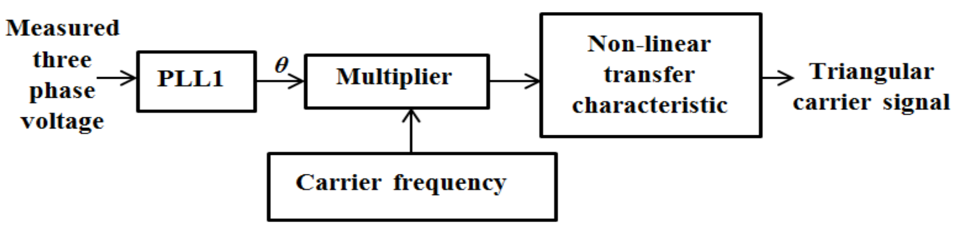


Figure 3.16: Model of PLL1 for generating triangular carrier signal.

The PLL1 is used for generating a triangular carrier signal. Firstly, the three phase voltage is measured and then it is delivered to the PLL1 for measuring phase angle θ and angular position of the voltage and then a carrier frequency is multiplied with this for getting a triangular waveform from a ramp waveform as shown in Fig. 3.16. In PLL2, the angle order (δ) is the output of PI controller and it represents the required shift between system voltage and voltage produced by the STATCOM/BESS. This shift of δ governs the direction and quantity of the real power flow and also used for the battery charging and discharging conditions as well as the power proportionality between dc link capacitor and BESS. The measured voltage (V_{pu}) in per unit is combined with a real constant and then put it to the maximum block for getting the maximum voltage wave form. The signal appends to a low pass filter for attenuating the signal transient. The error signal (V_{error}) is measured by comparing the voltage waveform to a reference one and then it is sent to the lag-lead functional block and then PI controller as shown in Fig. 3.17.

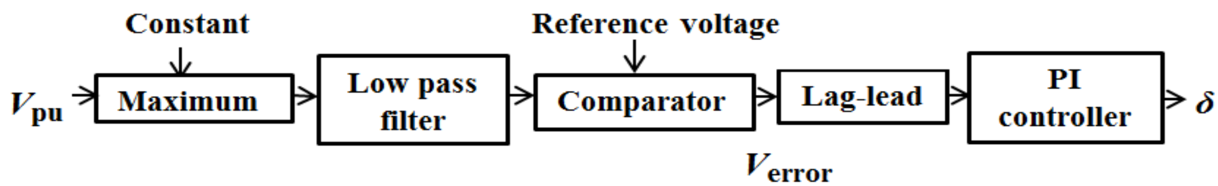


Figure 3.17: Model of voltage control loop.

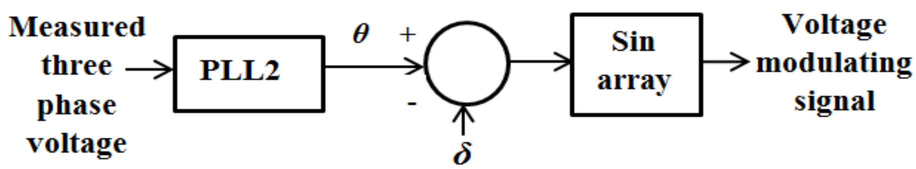


Figure 3.18: Model of PLL2 for generating voltage modulating signal.

Lastly, the combination of the δ and the synchronized voltage waveform generates a sinusoidal voltage modulating waveform as shown in Fig. 3.18. The output from the PLL1 (triangular wave form) and PLL2 (voltage modulating waveform) provides the necessary switching signal to the gate turn-off thyristors (GTO) (Fig.3.19).

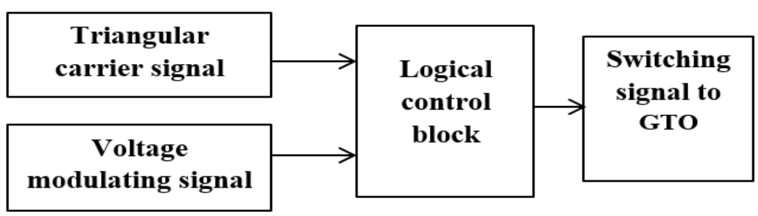


Figure 3.19: Model of generating switching signal.

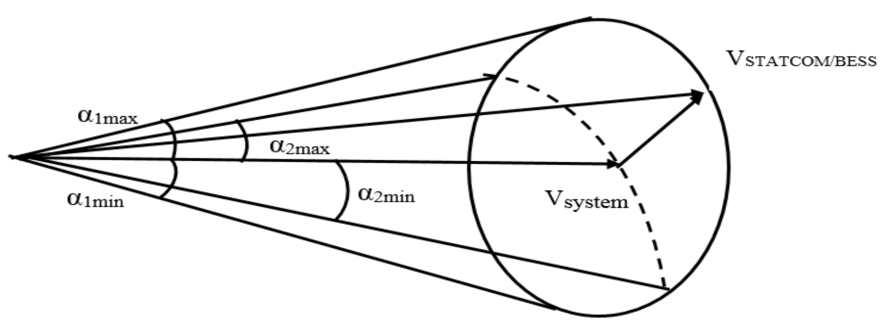


Figure 3.20: STATCOM/BESS voltage characteristics.

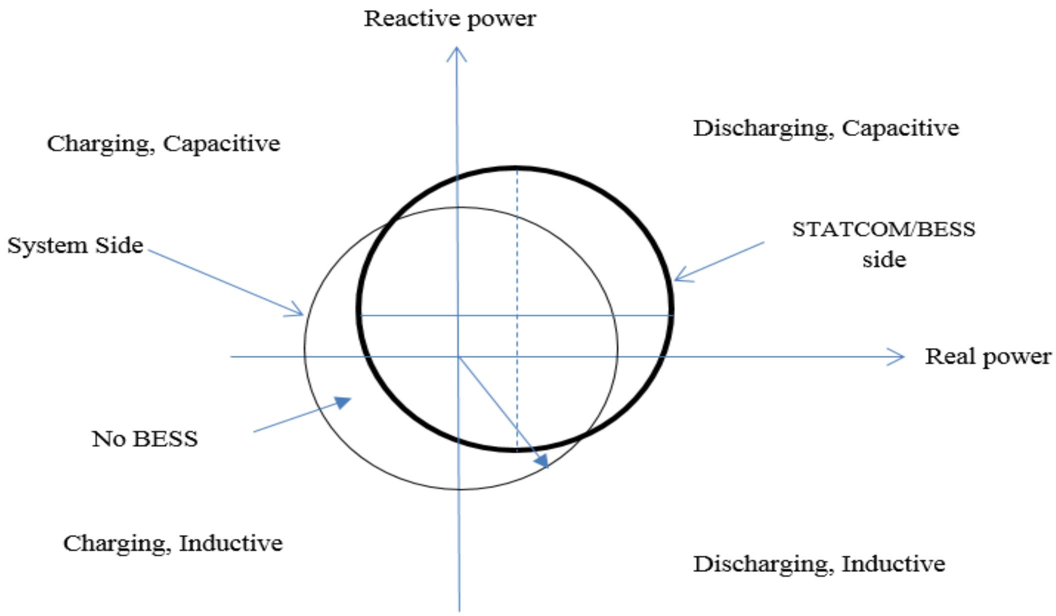


Figure 3.21: Four quadrant operation mode of STATCOM/BESS.

The common nature of BESS is, it cannot just operate in one mode infinitely means the battery cannot always be discharging; it must be charged after fully discharged. That's why the STATCOM/BESS also changes its operational mode time to time. This is known as the quasi steady- state operation. But this depends on the inverter voltage (V_i) and system voltage (V_s). When the system has more power that it needs, at that time battery collects it and discharge it when there is a less power in the system. However, discharging and charging profile simply enough to maintain stability of the power system. This sources can maintain the workability until any permanent source is brought to the system. The steady state operation of the STATCOM/BESS can be described with the Fig. 3.20. While going through the figure, it should be kept in mind that the output voltage of the traditional STATCOM is one dimension only. The value of output voltage of the traditional STATCOM must lie within the dashed line. On the other hand, the range of this output voltage of STATCOM/BESS can be any value within the circle. Thus STATCOM/BESS has more freedom of working region. The dashes line of the traditional STATCOM operational curve separates the STATCOM/BESS operating reason in to two reasons. For STATCOM/BESS the upper portion of the dashed line represents discharge area and lower left area represents the charging area. The $\alpha_{1\ maximum}$, as well as, $\alpha_{1\ minimum}$ are the maximum and minimum output voltage angles of STATCOM/BESS.

And the $\alpha_{2\ maximum}$ and $\alpha_{2\ minimum}$ are the maximum and minimum angles of output voltage of the traditional STATCOM.

From the representation Fig. 3.21, the active and the reactive power characteristics are shown under constant terminal voltage. One circle represents the possible output of the STATCOM/BESS and another circle represents the system side. The STATCOM/BESS side is shifted outward. The dashed line depicts the output of traditional STATCOM. Under ideal condition, STATCOM/ BESS can be operated within the circular region. Note that on the system side of the traditional STATCOM (the dashed arc), the active power is always negative on the system side. It means tradition STATCOM needs to draw active power from the system itself to compensate the losses that takes place in the system.

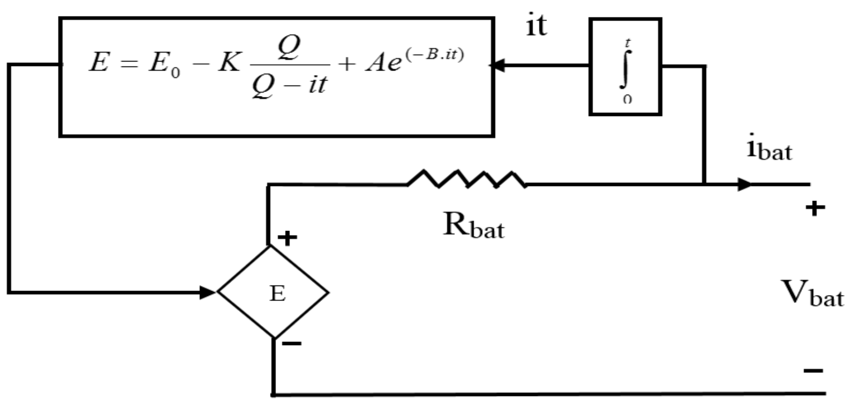


Figure 3.22: Battery model.

Here, E= No-load voltage [V], E_0= Battery constant voltage [V], K= Polarization voltage [V], Q= Battery capacity [Ah], A= Exponential zone amplitude [V], B= Exponential zone time constant inverse [1/Ah], $\int idt$ = Actual battery charge [V].

Electrochemical batteries (rechargeable batteries) are of great importance in power systems because they provide a means for storing small quantities of energy that is easily accessible if needed. The battery system installed in power grids for compensating the active and the reactive power. This method is a general approach, in which an ideal controlled voltage source, in series with a resistance, is used to model the battery. The value of the resistance is assumed to be constant. A non-linear equation (shown below) is used in the actual state of the battery to calculate the no-load voltage (Fig. 3.22).The battery voltage equation can be modified as follows in order to be expressed in terms of state of charging (SOC) instead of *it*:

$$E = E_0 - K.\frac{1}{SOC} + A.e^{-B.Q.(1-SOC)} \quad (3.13)$$

During the charging and discharging cycles, the internal resistance is assumed to be constant. The amplitude of the current does not have any effect on the capacity of the battery (No Peukert effect).

3.6 Model of DN

Generally, DNs deal with delivering electricity to the customer from a centralized power system and the today's advancement takes some changes in this trend and often using for collecting the power from the DG and this trend reduces the transmission loss as well as the cost.

Table 3.2: Line and load data of 12 bus radial system.

Line data				Load data		
From bus	**To bus**	**Reactance, X (in Ω)**	**Resistance, R (inΩ)**	**Bus no.**	**Active power load, PL (kW)**	**Reactive power load, QL (kVAR)**
1	2	1.093	0.455	1	0	0
2	3	1.184	0.494	2	60	60
3	4	2.095	0.873	3	40	30
4	5	3.188	1.329	4	55	55
5	6	1.093	0.455	5	30	30
6	7	1.002	0.417	6	20	15
7	8	4.403	1.215	7	55	55
8	9	5.642	1.597	8	45	45
9	10	2.890	0.818	9	40	40
10	11	1.514	0.428	10	35	30
11	12	1.238	0.351	11	40	30
-	-	-	-	12	15	15

The DG is a method of producing power from a small-scale energy source which is fed to the DN and it is called decentralized energy generation system or onsite generation. In this paper, a 12 bus radial distribution network is designed for analysis the power quality effects where B represents bus and L represents load as shown in Fig. 3.23. The 12 bus radial system's line data and load data are given in Table 3.2 [79].

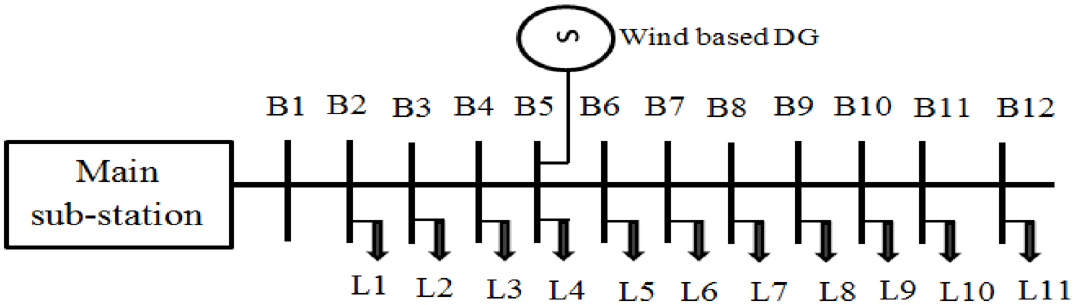


Figure 3.23: 12 Bus radial network with wind power based DG.

In this 12 bus radial system, different types of loads are connected where some loads are non-linear in characteristics and they introduce harmonics in the system and when the DN consist DG connection then the power electronics devices of DG system contribute a lion share of harmonics in this and the situation becomes vulnerable. The voltage between any two phases of DN is 400 V and any phase and neutral is 230 V.

3.7 Summary

The model developed in this research is well oriented. This model creates the scope to popularize the wind based DGs accompanied with DNs. A proper integration between AC/DC/AC converter and STATCOM/BESS control mechanisms creates a stable system and this model is capable to mitigate all power quality issues effectively.

CHAPTER IV

Solutions of Power Quality Problems Using Proposed Method

4.1 Introduction

Power industry is always looking towards the advance and upgraded technologies and researchers are always trying to find out a perfect solution of different problems which takes the power system in a new dimension and for the same reason this research has done to remove the curse of harmonics from the power industry. The system is design to create a practical situation, for this reason, the wind based DG is fed to a DN. Then after identifying and understanding the problems clearly, a solution is given which is very much effective to reduce all the problems by this one solution. So that power industry can easily construct this model which takes the world towards sustainability.

4.2 Harmonics Analysis in Laboratory

In the laboratory various experiment is performed for measuring the harmonics level of different loads with the help of harmonic analyzer. This is done for understanding the harmonics effects. Very common types of loads are taken into the consideration which are always used in the households and industries. When this loads are connected with the DN then for avoiding the uncertain circumstances there must have to present different solutions in the system. For removing different problems different types of devices with specific control mechanism are added in the system. However, this research gives a solution which is able to mitigate all the problems by using only one device with proposed control mechanism which will decrease the complexity of the circuit.

Case 1: The tube light with magnetic ballast is taken to the consideration for harmonic analysis (Fig. 4.1) and it is found that the current THD is only 16.7% and if the setup is arranged with tube light with electronics ballast than the current THD is increased at 132.4%

as shown in Fig. 4.2. So it is proved that power electronics devices increased the harmonics level in the system.

Figure 4.1: Total setup of the harmonic analysis of a tube light (magnetic ballast).

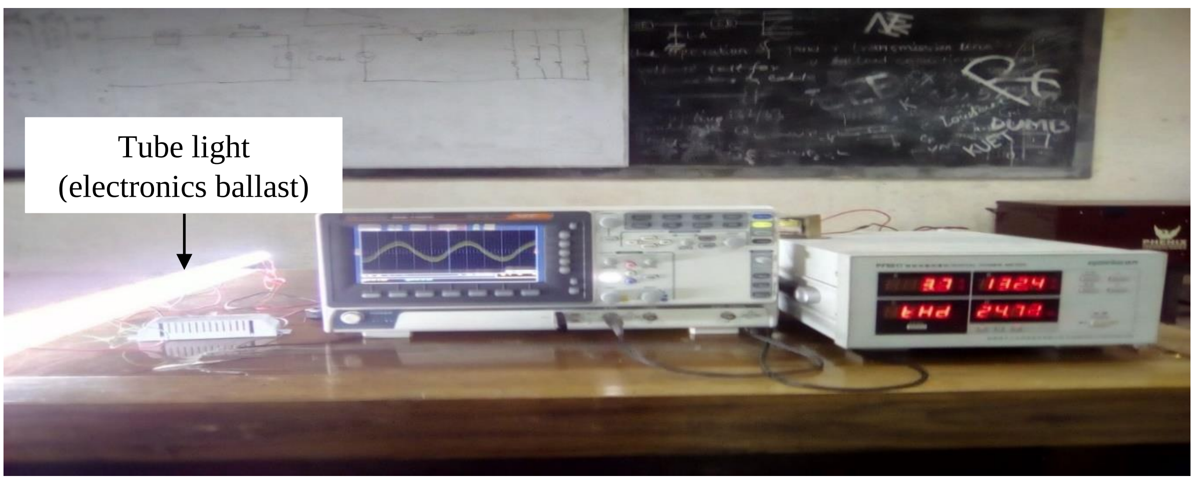


Figure 4.2: Total setup of the harmonic analysis of a tube light (electronics ballast).

Figure 4.3: Total setup of harmonic analysis of a battery supplied inverter with load.

Case 2: When an inverter is supplied by a battery where a load (100W bulb) is connected at this time, it is observed that the current THD is 25.7% as shown in Fig. 4.3. After that if the inverter is supplied by the line supply at that moment the current THD level is increased dramatically that is 120.6% as shown in Fig. 4.4, because at this time an AC to DC converter is added before the connection of the inverter.

Figure 4.4: Total setup of harmonic analysis of a line supplied inverter with converter and load.

In the same way other analyses are done in the laboratory with different load conditions and from Table 4.1, it is proved that the level of harmonic is different in every case.

Table 4.1: Harmonic analysis of different load in laboratory

Harmonics analysis	Current THD (%)	Voltage THD (%)
100 W bulb	2.7	3.2
Table fan	58.2	2.4
Bridge rectifier	42.5	2.4
Converter	148	2.5

4.3 Harmonics Problems

A wind based DG system when connected to the DN as an onsite generation system then the total power of the DN is increased with this additional power. However, the wind turbine cannot connect to the DN directly and in between this, electronics converters are added for voltage and frequency issues and these converters badly affect the power quality and a distorted version of power is added to the DN. Though the wind turbine produce a harmonics free power but a polluted power with harmonics is pushed to the DN due to this converter. For understanding the harmonics generation rate in the system, various situations are examined with different types of load and DG connection.

For different case studies different non-linear loads are designed. Firstly, A 40 HP induction motor with an adjustable speed drive (ASD), as shown in Fig. 4.5 is designed, and connected at bus 5 for the analysis. In this motor drive, the PWM technique is applied for controlling the 6-pulse inverter of the ASD which is the main source of harmonics generation. Generally, for its construction, in an induction motor two types of harmonics are introduced; one is space harmonic and the other one is time harmonic [80]. Space harmonics are generated in the circuit for the interaction of different phase winding at the time of rotating magnetic field generation. This space harmonics cause various problems like generation of noise, vibration and affect the starting of the motor. On the other hand, the time harmonics generate heat which is very harmful for the system. The addition of ASD's harmonics, this harmonics pollution reached to an extreme level. In this system, a 6-pulse bride rectifier and a dc link capacitor is also used. The inverter of the ASD converts the dc voltage to ac voltage to control the motor's speed.

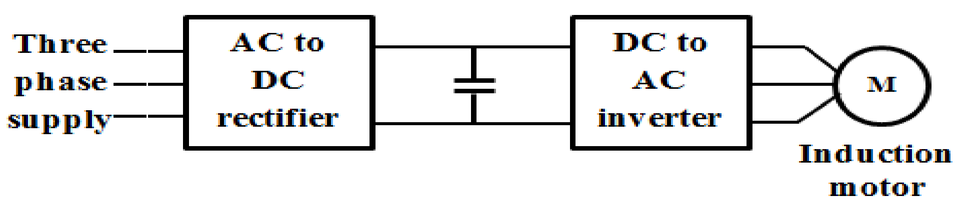


Figure 4.5: Model of induction motor with ASD.

The electric arc furnace is another major non-linear load which is commonly used in steel industry for melting and refining purposes. This device is used for melting metal by converting the electrical energy to an electric arc. However, it produces harmonics in the system for the highly non-linear V-I characteristics of arc. The harmonic effect is large because of its large capacity lumped together at one place. When this load is connected to the system, it hampers the power quality of the system. Voltage harmonic distortion is prominent in this load than the current harmonics [81]. Practically, the V-I characteristic gives more noise due to the unpredictable and chaotic nature of the load. This model of arc furnace is based on a non-linear differential equation [82].

$$k_1 \cdot r^n + k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} \cdot i^2 \qquad \text{.............. (4.1)}$$

$$v = \frac{k_3}{r^{m+2}} \cdot i \qquad \text{................................. (4.2)}$$

here, i = arc current, v = arc voltage, r = arc radius. The parameters k_i ($i=1, 2, 3$), r and n characterize the arc under a given operating condition.

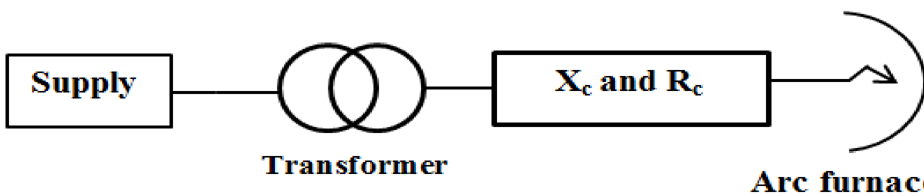


Figure 4.6: Online diagram of an arc furnace.

An arc furnace is connected at bus 5 of the DN as shown in Fig. 4.6. Here, X_c and R_c are the reactance and resistance, respectively of the connecting line to the arc furnace electrodes.

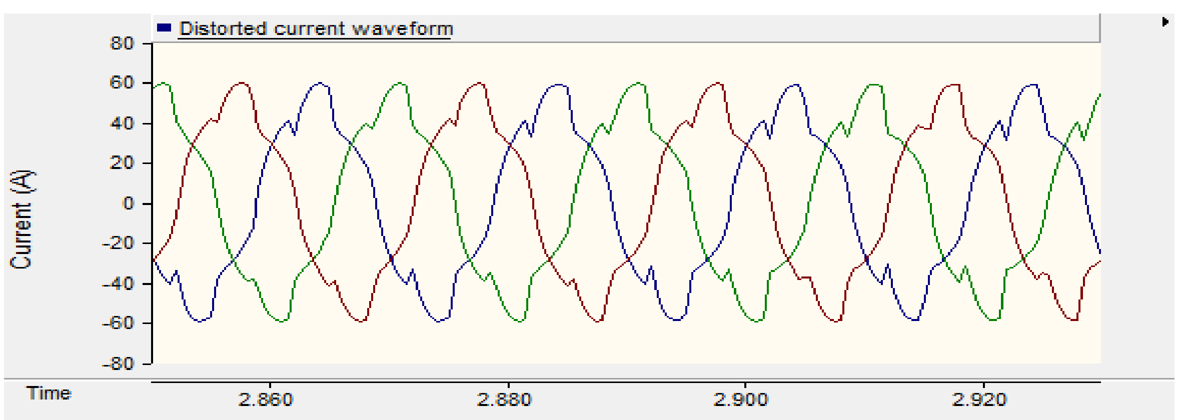


Figure 4.7: Distorted current waveform due to RL load and DG's converter.

Case 1: When the RL load is implied with the system at bus 5, the harmonics of the DG's converter and RL load are merged and the resultant harmonics go beyond the tolerable limit. In normal operating condition, an RL load produces less harmonics and the individual harmonic of the system mostly comes from the converter of DG. From this analysis, it is observed that in case of RL load, the current harmonics are higher than the voltage harmonics. The distorted current waveform in this case is shown in Fig. 4.7. Generally, in DN several DGs are connected for collecting more power. If the number of DG is increased in the system then the harmonic level is also increased, as shown in Table 4.2, because of increasing the number of power electronics based converters.

Table 4.2: Individual harmonic distortion (in %) of the system during RL load with single and three DG unit.

Harmonic order	**RL load with single DG unit**		**RL load with three DG unit**	
	Individual current harmonic distortion (in %)	**Individual voltage harmonic distortion (in %)**	**Individual current harmonic distortion (in %)**	**Individual voltage harmonic distortion (in %)**
3^{rd}	3.925	2.331	11.761	9.843
5^{th}	19.148	15.394	63.653	49.975
7^{th}	16.921	13.283	46.212	38.274
9^{th}	14.991	9.937	28.559	20.345

When the STATCOM / BESS is added in the system, the level of distortion is decreased and the current waveform becomes sinusoidal as shown in Fig. 4.8.

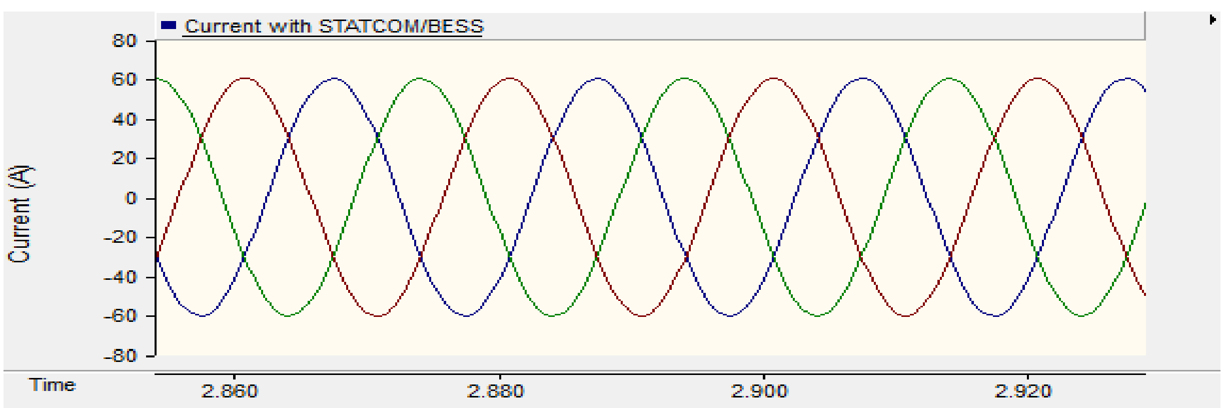
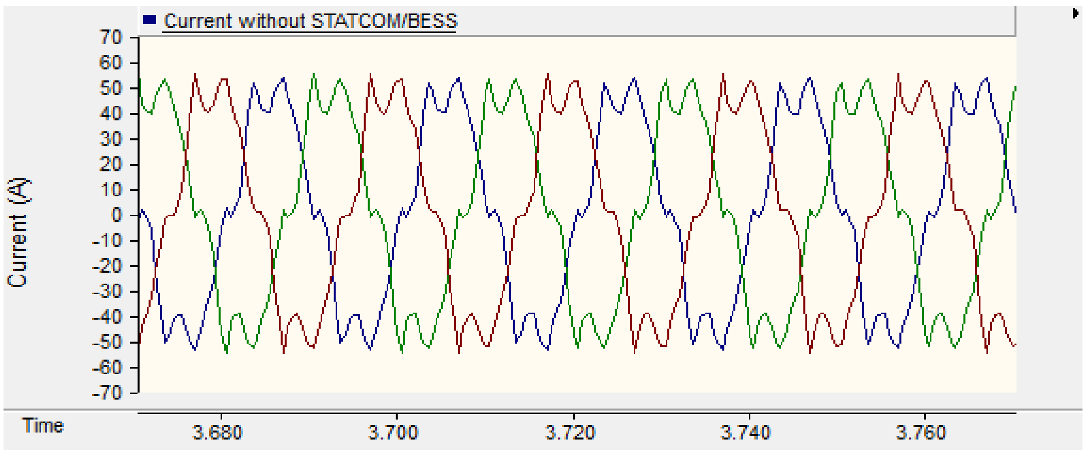
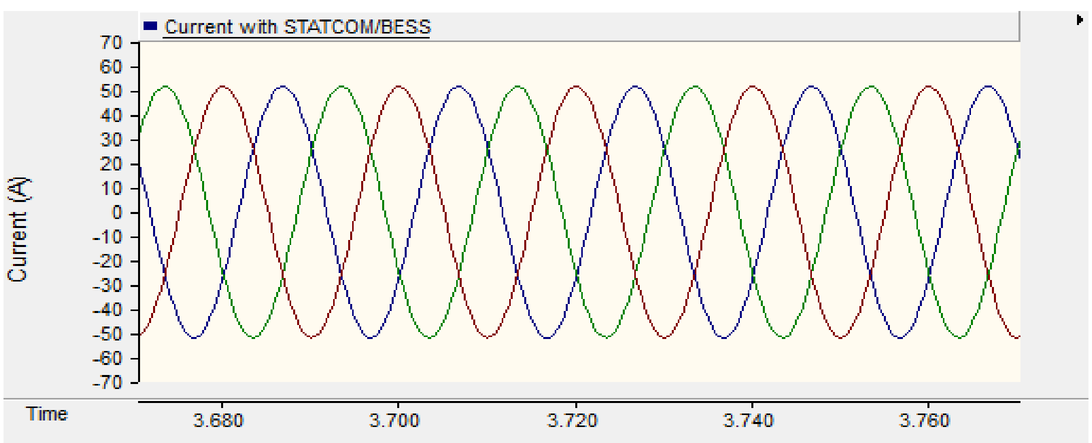


Figure 4.8. Current waveform with RL load with STATCOM/BESS connection.

Case 2: If the induction motor with ASD is incorporated in the system, an excessive magnitude of harmonic is generated because this ASD contains a power electronic inverter. In this case, the current is more affected by the harmonics and both current and voltage harmonics are more than that of the RL load. The combination of the induction motor's harmonics, ASD's harmonics and the DG converter's harmonics create a vulnerable situation in the system. When the STATCOM/BESS controller is made ON, it mitigates harmonics of the DG integrated system. Figures 4.9 and 4.10 portray the load side (L4) current and voltage waveforms without and with STATCOM/BESS and Fig. 4.11 shows the Fast Fourier Transform (FFT) analysis of individual harmonic distortion (in %) of load side current and voltage, and it is clear that the proposed model with this control mechanism is very effective for harmonics reduction of the DN.

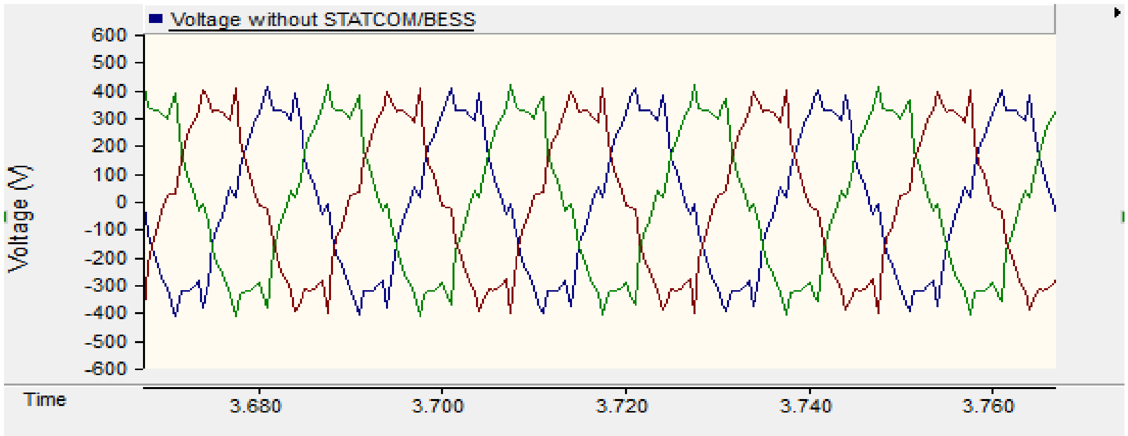


(a)

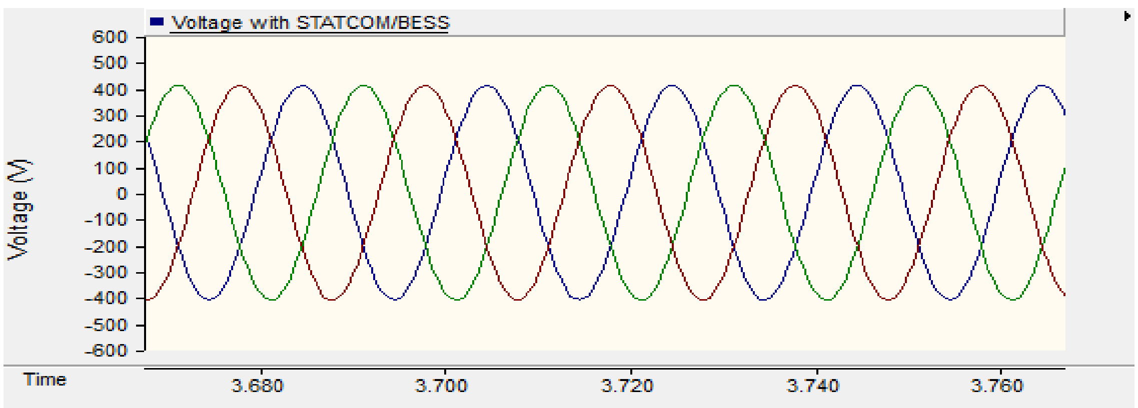


(b)

Figure 4.9: (a)Distorted current waveform due to induction motor with ASD and AC/DC/AC converter of DG, (b) Current waveform with STATCOM/BESS.

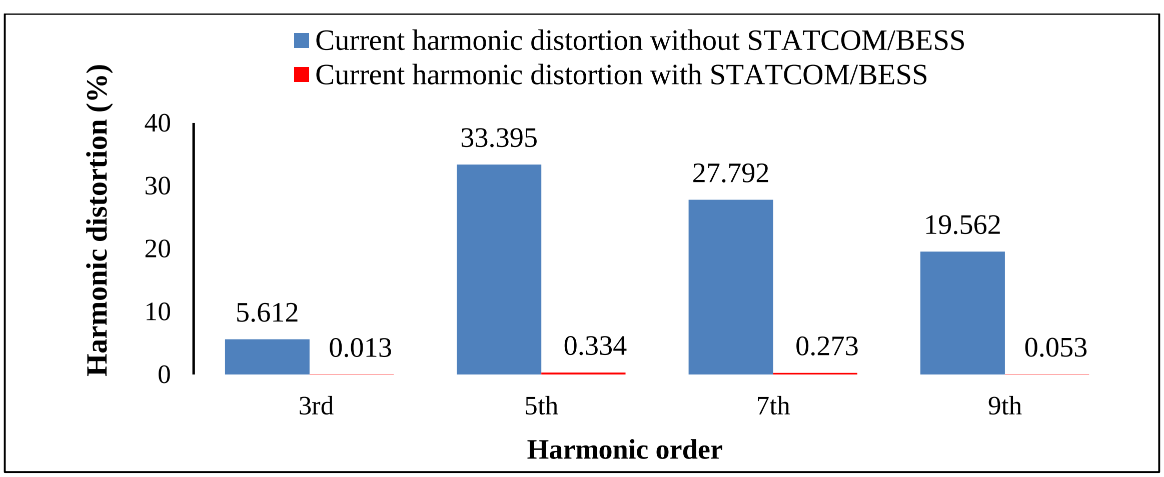


(a)

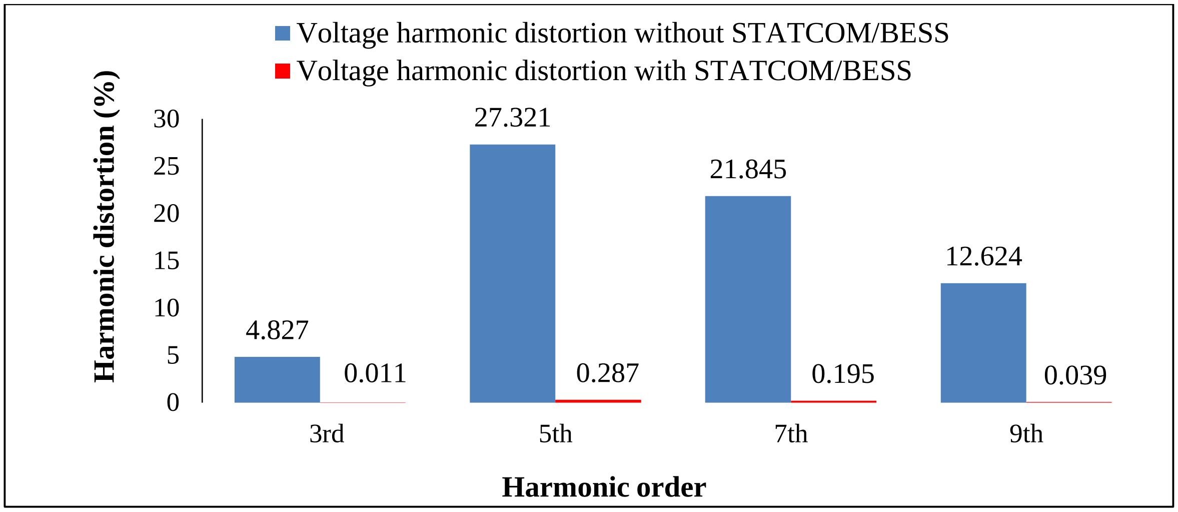


(b)

Figure 4.10: (a) Distorted voltage waveform due to induction motor with ASD and AC/DC/AC converter of DG, (b) Voltage waveform with STATCOM/BESS.



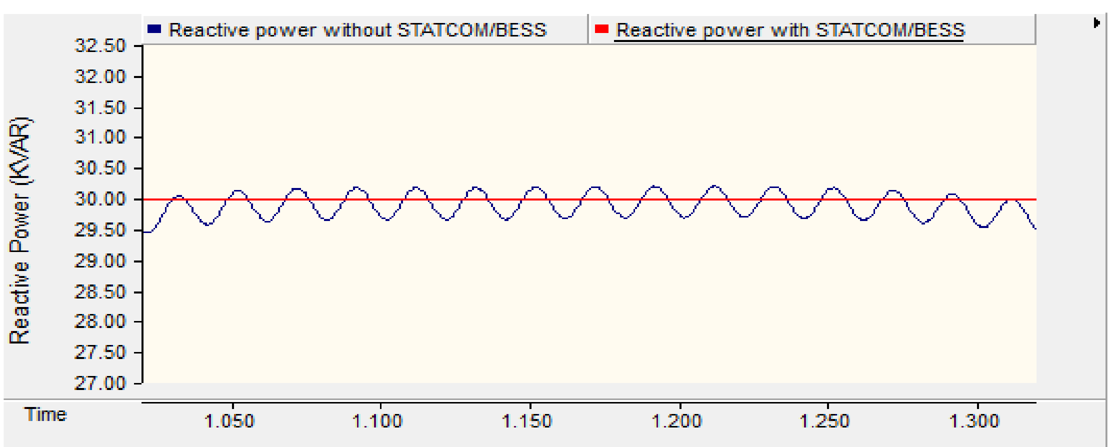
(a)



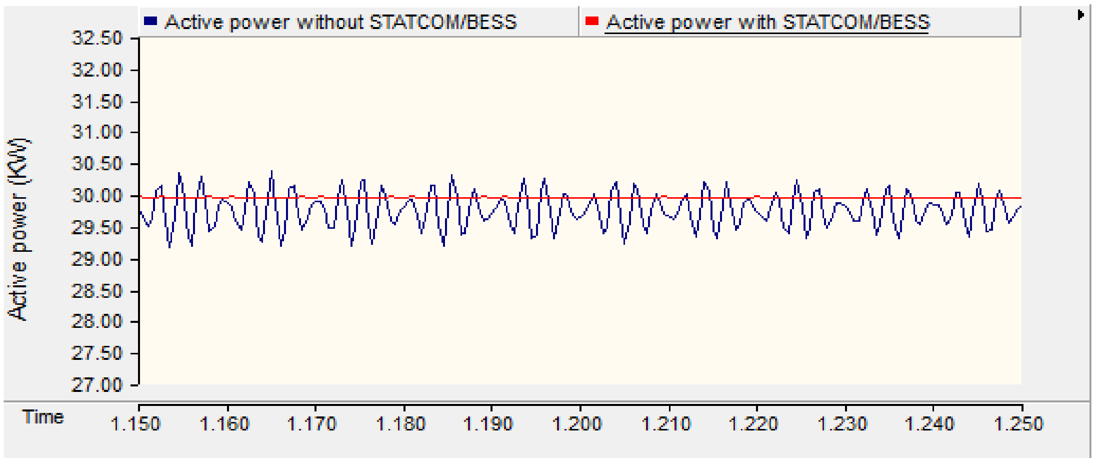
(b)

Figure 4.11: (a) Individual current harmonic distortion (in %), (b) Individual voltage harmonic distortion (in %).

Power stability of the system is a common and important issue. For getting a stable reactive power STATCOM can be a solution but it can not give the real power support. For this reason, STATBOM/BESS is the best solution for the power stability. From the Fig. 4.12, it is clear that without STATCOM/BESS the active and reactive power is unstable but after adding a STATCOM/BESS in the system, both power become stable.



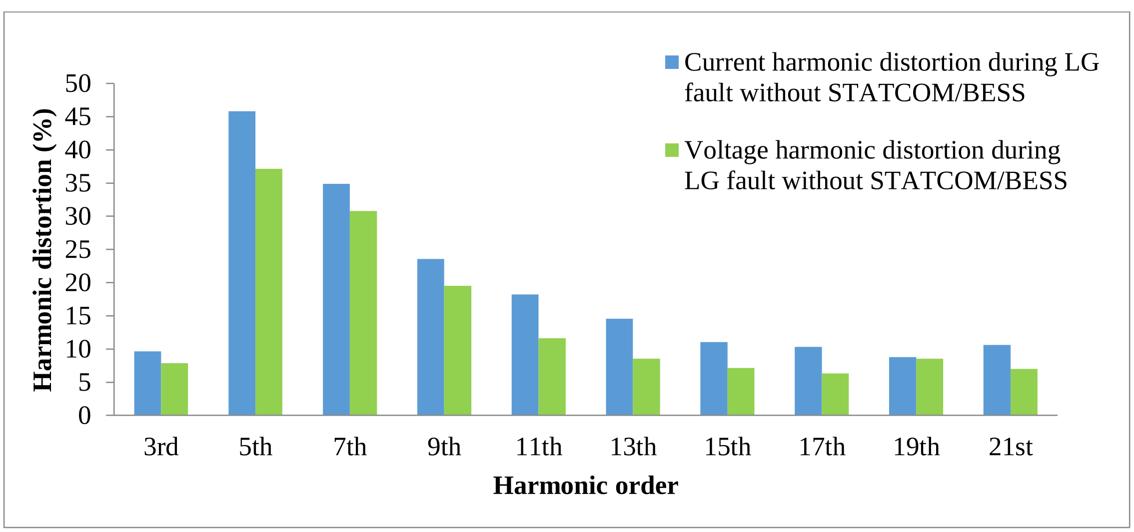
(a)



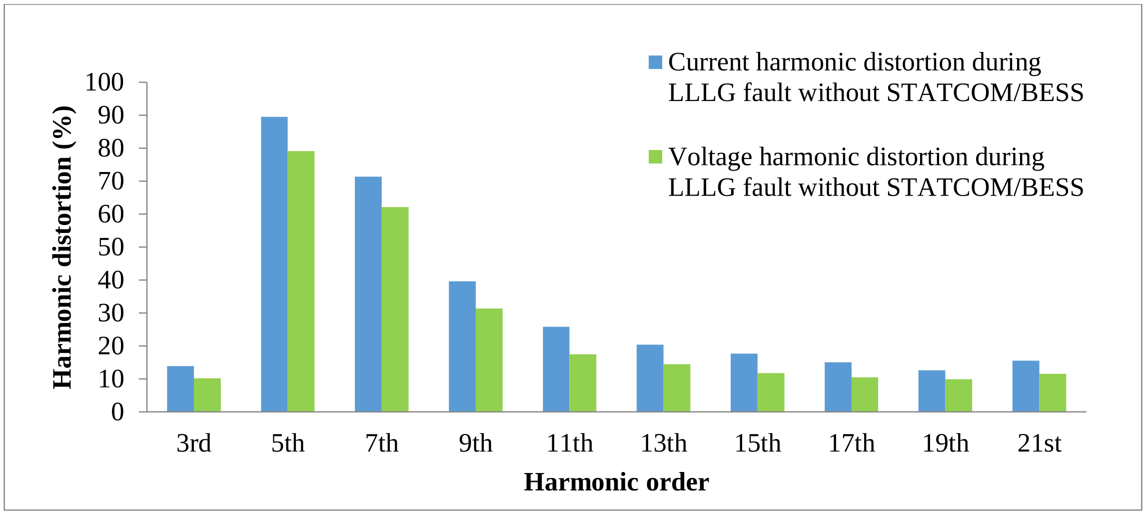
(b)

Figure 4.12: (a) Active and (b) reactive power with and without STATCOM/BESS.

Case 3: The level of interrupted harmonics of the converter and the non-linear loads is increased when the system faces any kinds of faults as shown in Fig. 4.13. During single line to ground (LG) fault the level of harmonic is raised but it reaches to the extreme level in case of three-phase (LLLG) fault which may damage a significant portion of the system. This representation again proves that an LLLG fault is the most severe fault in case of harmonics. In the system, a fault is applied at bus 12 for 0.2 second.



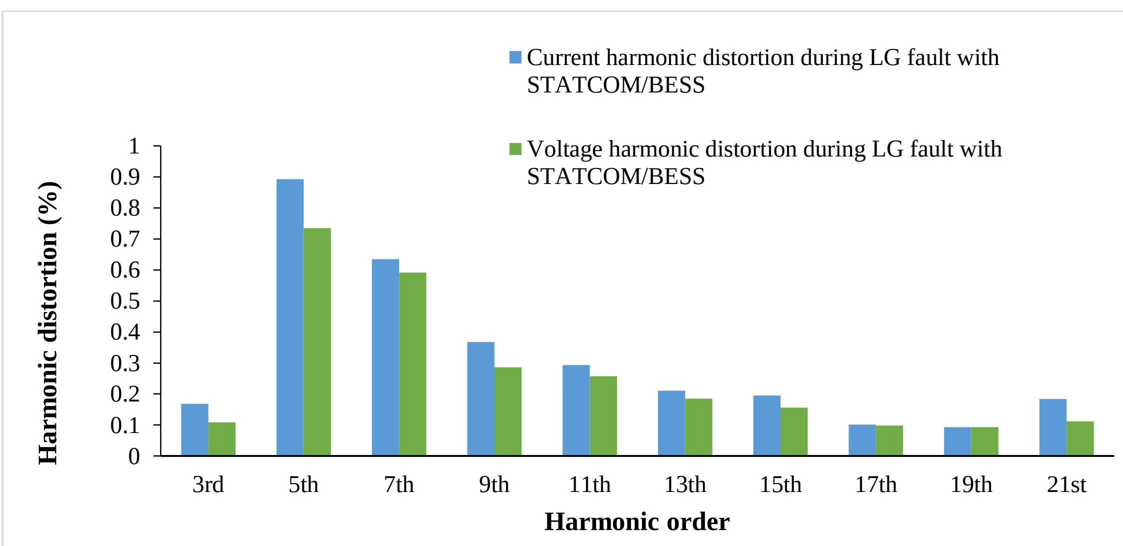
(a)



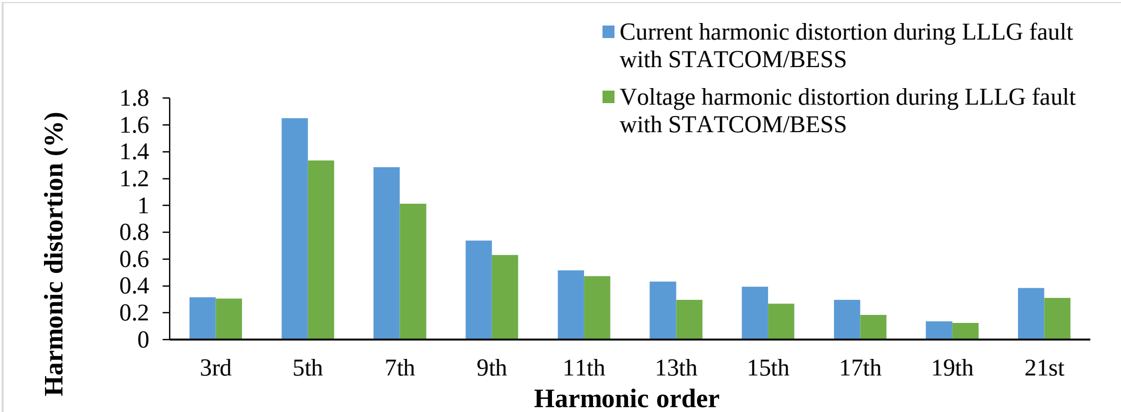
(b)

Figure 4.13: Individual current and voltage harmonic distortion (in %) of induction motor with ASD and DG's converter during fault.

By connecting a STATCOM/BESS in the system, it is possible to keep this high level of harmonics within a safe limit as shown in Fig. 4.14.



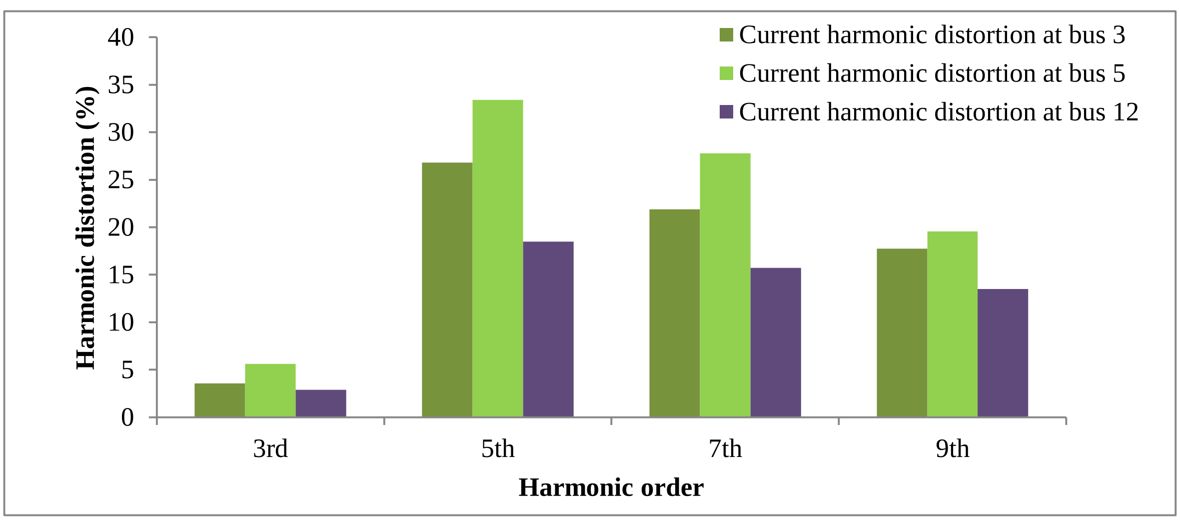
(a)



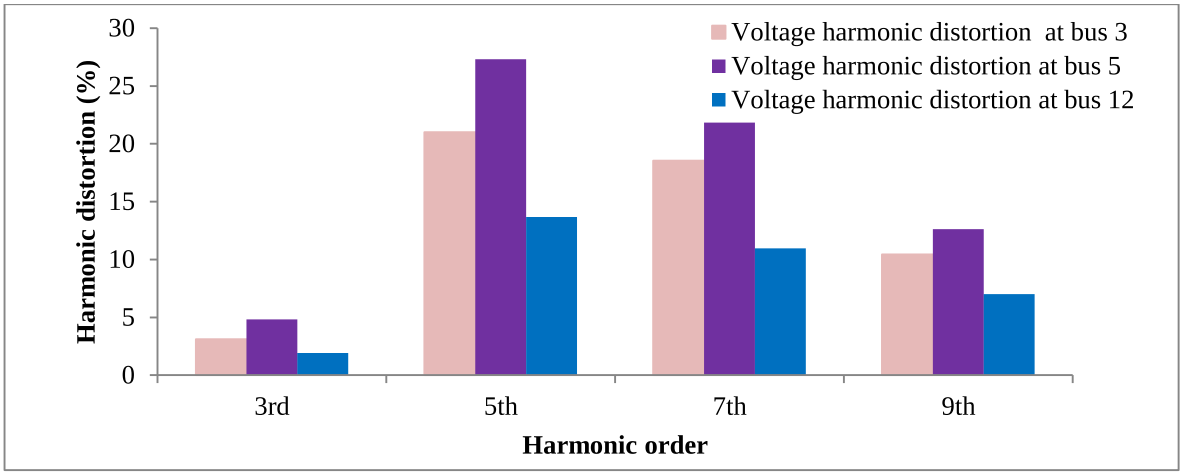
(b)

Figure 4.14: Individual current and voltage harmonic distortion (in %) during fault with STATCOM/BESS.

Case 4: The positioning of the DG is an important factor in harmonics analysis. The position of it determines the magnitude of harmonics. The far the DG from the non-linear load, the minimum amount of harmonics is generated and vice-versa. If the non-linear load and the DG are connected at the same bus that is bus number 5, then the highest magnitude of harmonics is generated. If the DG is connected at the far corner that is bus number 12, the harmonics are minimum. And, connecting the DG unit in a mid-position that is bus number 3, the generated harmonics also lie in the mid-range as shown in Fig. 4.15.



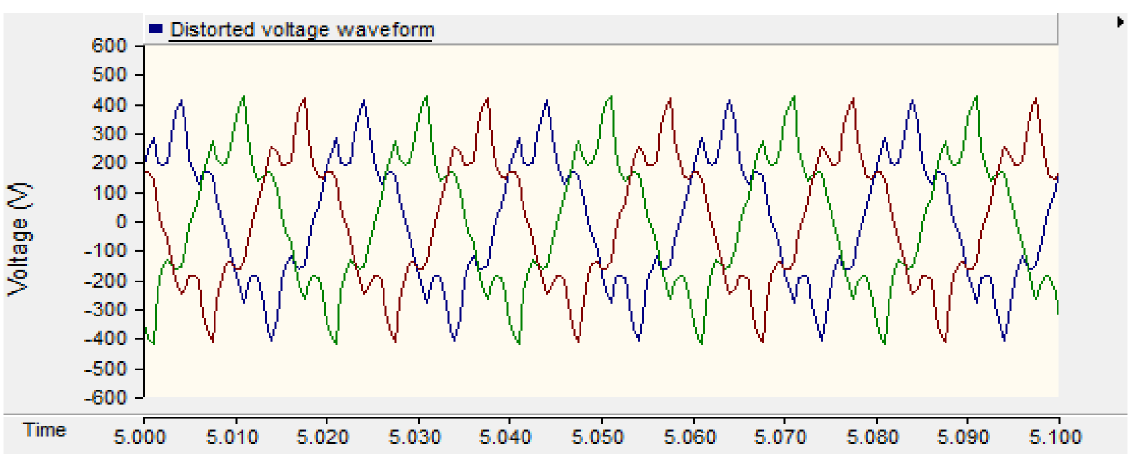
(a)



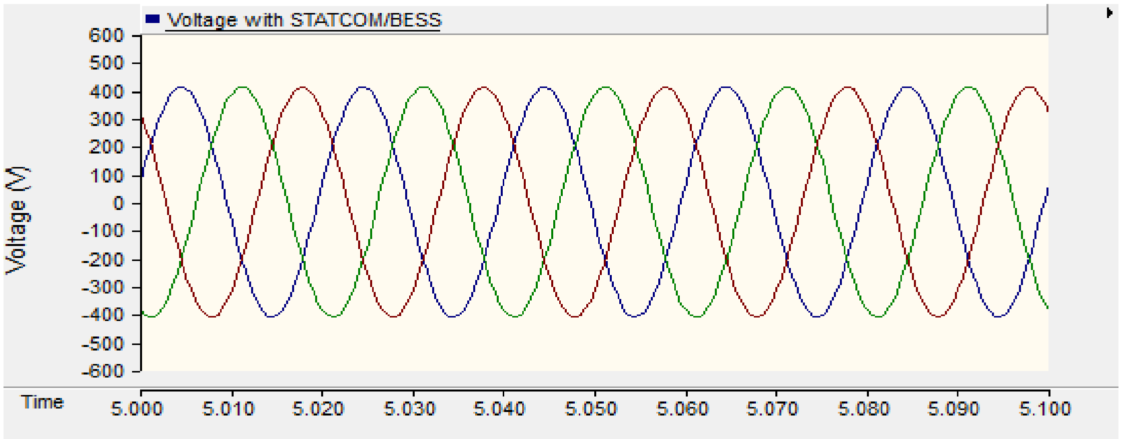
(b)

Figure 4.15: Individual (a) current and (b) voltage harmonic distortion (in %) of induction motor with ASD and DG's converter depending on DG's position.

Case 5: In this part, an arc furnace is taken into consideration for harmonic analysis. It is connected at bus 5. The voltage harmonics are the major harmonics in this case. From Fig. 4.16 (a), it is seen that the voltage wave form is seriously affected by the harmonics. The DG's converter adds more contribution in harmonics pollution. Through this case study it is again proves that STATCOM/BESS has the ability to solve the arc furnace harmonic issues effectively given in Fig. 4.16 (b).

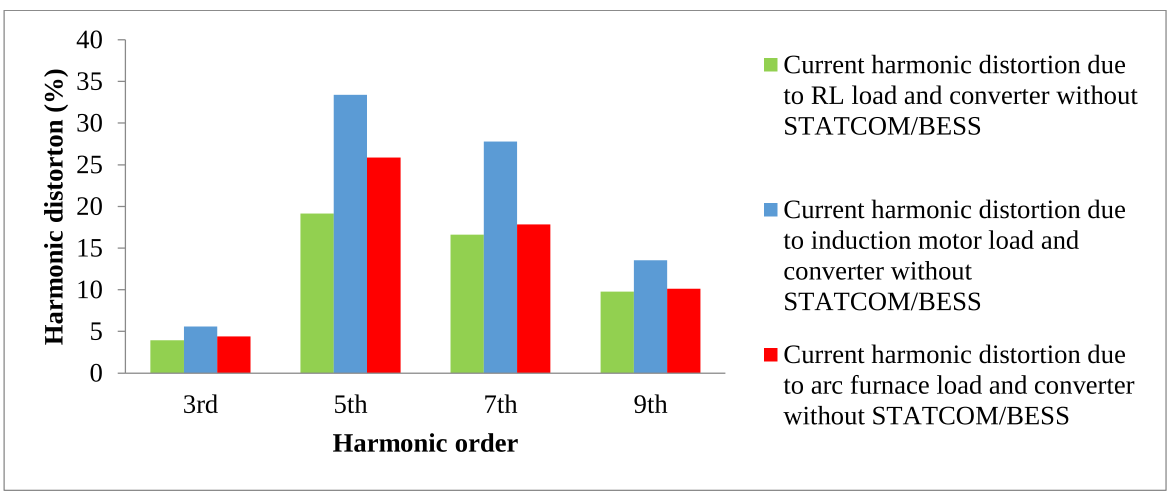


(a)



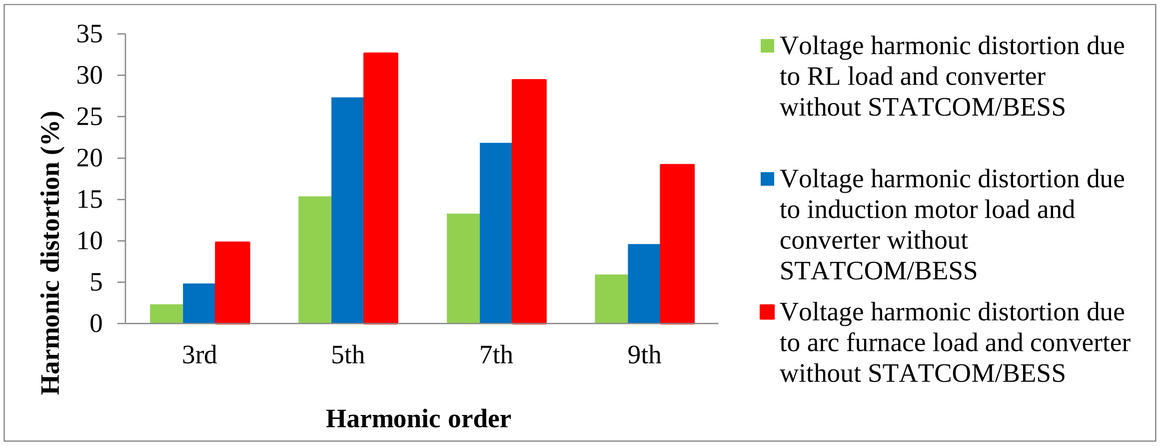
(b)

Figure 4.16: Distorted voltage waveform due to arc furnace and AC/DC/AC converter of DG (a)without and (b) with STATCOM/BESS.



(a)

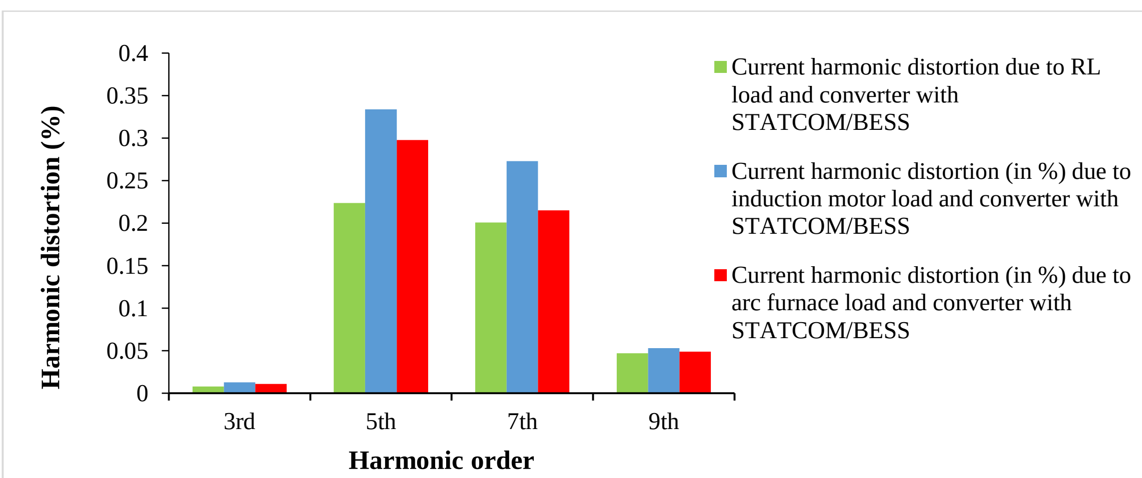
Case 6: In this part of the analysis, a comparison among the RL load, induction motor load and arc furnace load is overviewed and through graphical expression, it has been depicted. From Fig. 4.17, it is found that the induction motor is the most current harmonics generating device in comparison with RL load and arc furnace. On the other hand, the arc furnace produces more voltage harmonics than the other two types of loads. The RL load contributes less harmonics in both cases of current and voltage. From Fig. 4.17, it is observed that 5^{th} and 7^{th} are the most prominent harmonics in this system. According to IEEE Std 519-1992, the allowable individual voltage and current harmonic distortion are 3% and 4%, respectively [83]. In this test setup, voltage and current harmonic distortions of three types of loads exceed the tolerable limit set by the IEEE.



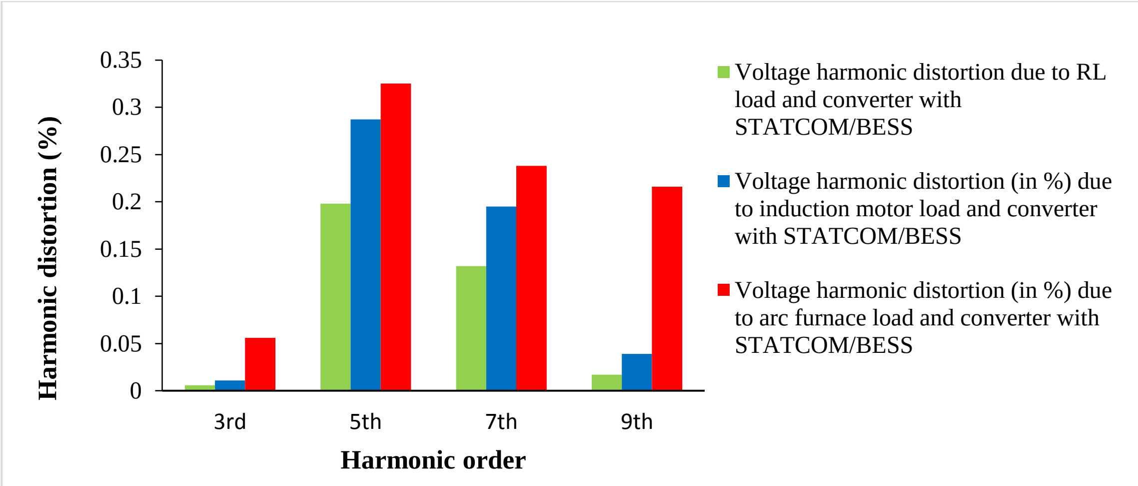
(b)

Figure 4.17: Individual (a) current and (b) voltage harmonic distortion (in %) due to three different non-linear loads with DG's converter without STATCOM/BESS.

Harmonics has become an extensively ameliorating problem in the wind farms and this proposed model is designed for the elimination of harmonics from the DG integrated system. The altimate solution is STATCOM/BESS with proposed control mechanisms for these kind of problems which is the finding of the research (Fig. 4.18).



(a)



(b)

Figure 4.18: Individual (a) current and (b) voltage harmonic distortion (in %) due to three different non-linear loads with DG's converter with STATCOM/BESS.

4.4 Voltage Sag and Swell

The voltage sag is another most common power quality problem which is caused for the unexpected fault, motor startup and short-circuit. It is also known as voltage dip which is the short term reduction of voltage from its rated value [84]. It is measured by seeing the depth and duration. For voltage sag analysis purpose, an induction motor with ASD is taken into consideration with the DG connection. If, after 3.7 second, an LG fault occurred in the test system at bus 12 for two-cycle then voltage sag is notified in the system as shown in Fig. 4.19. From this figure it can be observed that, only faulty phase A has fallen down during this time where the other two phases are also disturbed but it faces voltage swell which is the sudden increase of voltage from its rated value. This voltage swell problem is also taken place during the total time of voltage sag [85]. The STATCOM/BESS is also working for this problem and take the voltage level with in a safe range. STATCOM/BESS minimizes the voltage sag and mitigates the voltage swell at the same time as shown in Fig. 4.20.

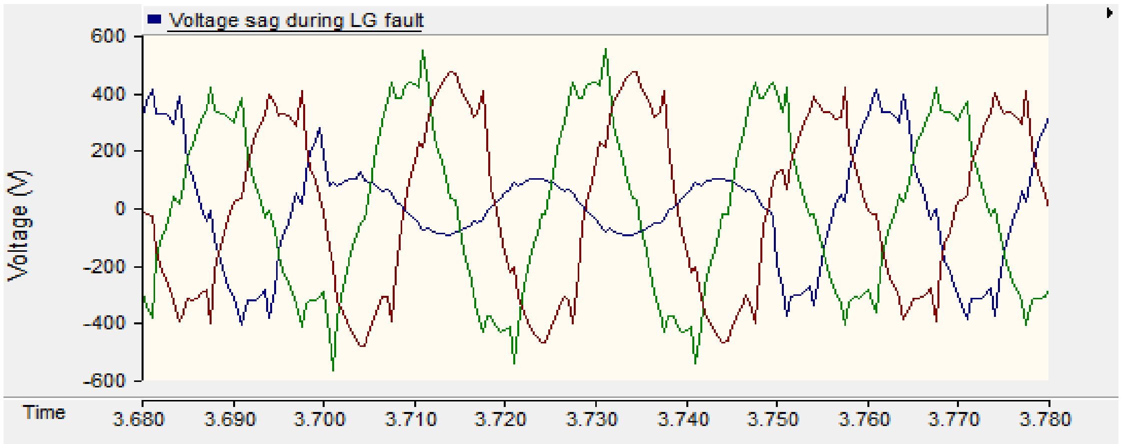


Figure 4.19: Voltage sag and swell during LG fault without STATCOM/BESS.

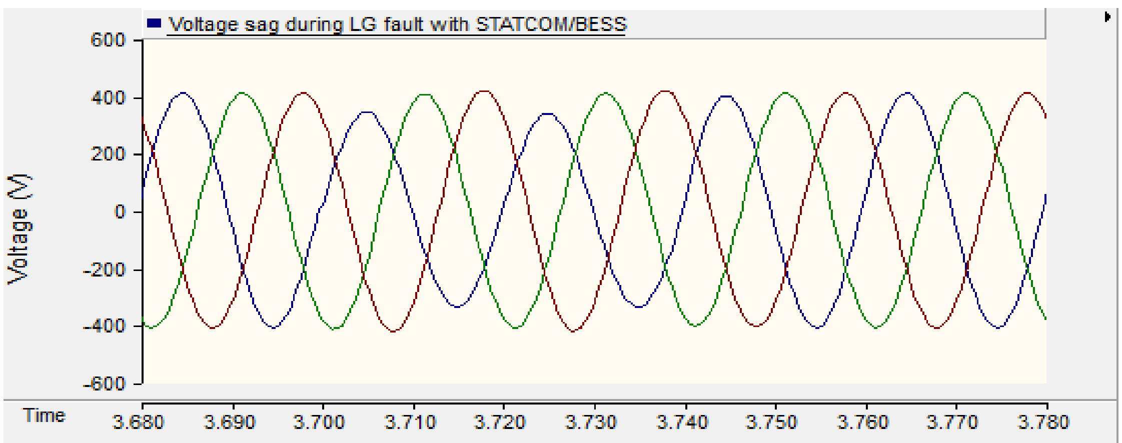


Figure 4.20: Voltage sag and swell during LG fault with STATCOM/BESS.

If, after 1 second, a three-phase fault (LLLG fault) occurs at bus 12 in the test system for 0.1 second then large voltage sag is notified in the system. From Fig. 4.21, it is seen that the STATCOM/BESS recovers the voltage profile of the system quickly after a disturbance. During LLLG fault, this voltage sag becomes 53% and it is reduced and recovered its rated value quickly when a STATCOM/BESS is connected and it becomes 85% sag. From this Figures, it is clear that this proposed model can reduce the voltage sag.

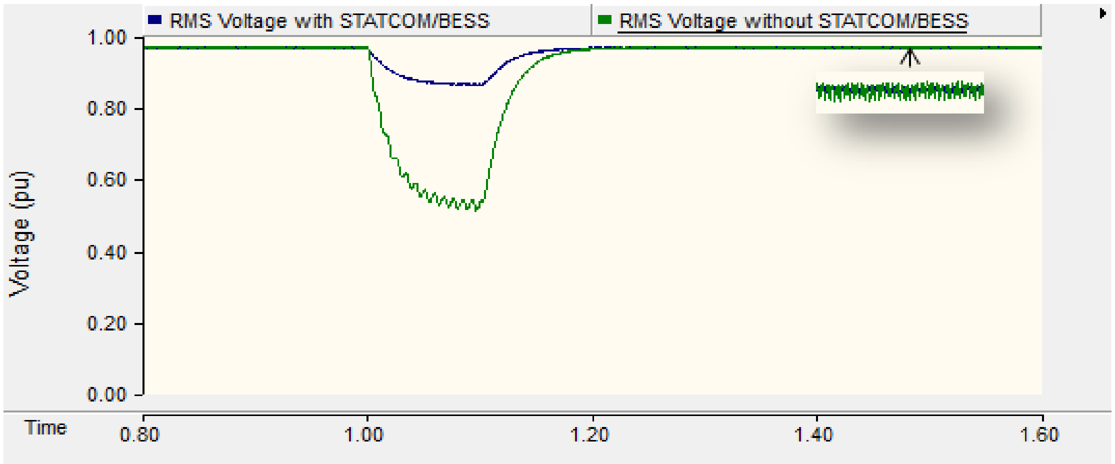


Figure 4.21: Voltage sag occurrence in the system due to LLLG and reduction of it with the proposed model.

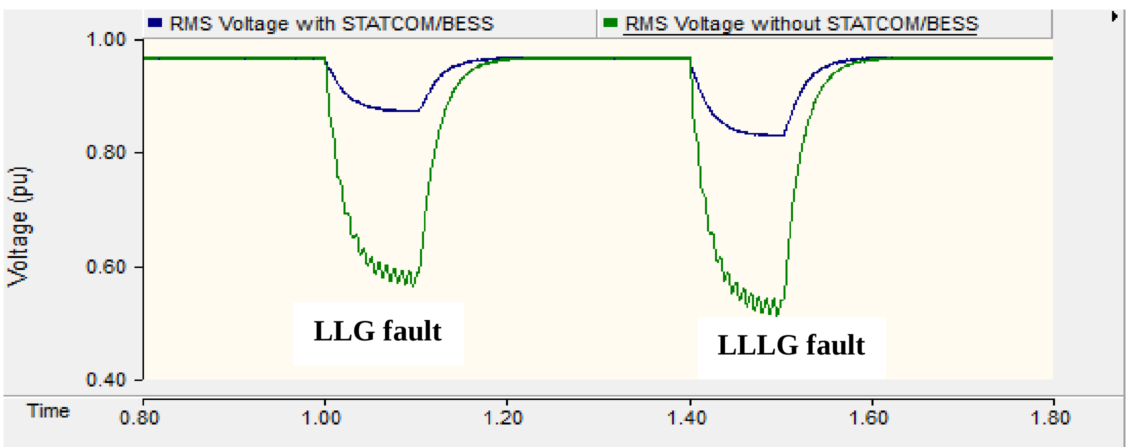


Figure 4.22: Voltage sag during repitive LLG and LLLG faults.

Sometimes, system faces repetitive faults and the traditional protecting devices are unable to face these repetitive faults and cannot take the action quickly. However, this control mechanism is designed in such a way that it can also perform against repetitive faults. If the double line to ground fault (LLG) and LLLG faults are occurred repetitively for 0.1 second at bus 12 then in case of LLLG fault the largest voltage sag is notified as 53% sag and during an LLG fault, the largest sag is 58% sag. When a STATCOM/BESS is employed in the system then the voltage sag is reduced and after the application, for LLLG fault the voltage sag is notified as 85% and during an LLG fault, 90% sag is observed as shown in Fig. 4.22.

4.5 Comparison between Proposed Method and Exiting Techniques

In this time an active filter (Fig. 4.23) is taken to the consideration and set this device in place of STATCOM/BESS. This active filter is controlled by hysteresis current PWM technique [86] and the control block is shown in Fig. 4.24.

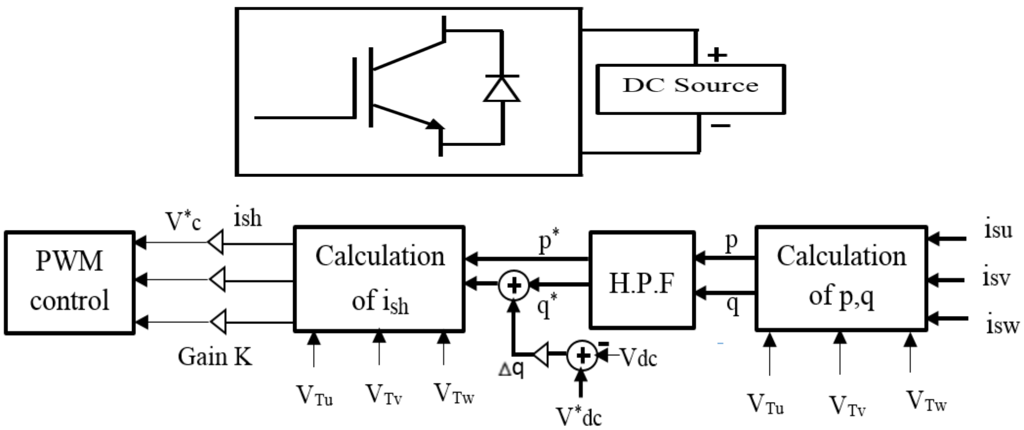


Figure 4.23: Active filter with hysteresis current PWM controller.

Three phase source currents, i_{su}, i_{sv}, and i_{sw} are detected and a source harmonic current in each phase i_{sh} is calculated by applying the p - q theory. The terminal voltages and the source currents are transformed from three phase to two phase quantities as follows.

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_u \\ e_v \\ e_w \end{bmatrix} \quad \text{(4.3)}$$

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{su} \\ i_{sv} \\ i_{sw} \end{bmatrix} \quad \text{(4.4)}$$

Here, e_u, e_v, and e_w, are the fundamentals of the terminal voltages V_{Tu}, V_{Tv}, V_{Tw} respectively. Hence, the instantaneous real power p and the instantaneous imaginary power q are given by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad \text{...} \quad (4.5)$$

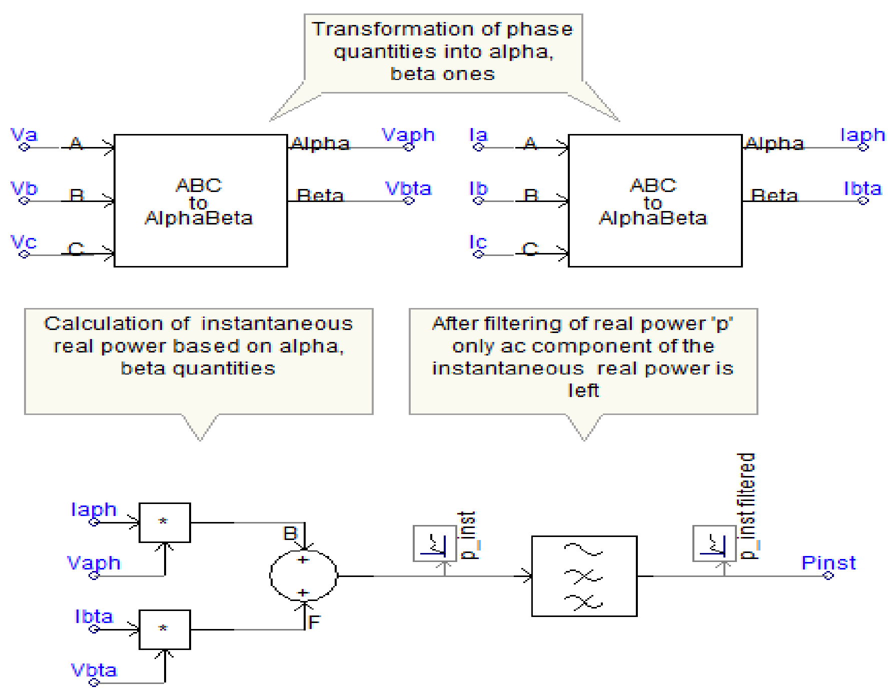
In (4.5), the i_{sh} is transformed to dc components p_{dc} and q_{dc}, and the harmonics to ac components p^* and q^*. The ac components are extracted by two high pass filters and the harmonics of the three phase source currents, i_{shu}, i_{shv} and i_{shw} are obtained by the following calculation:

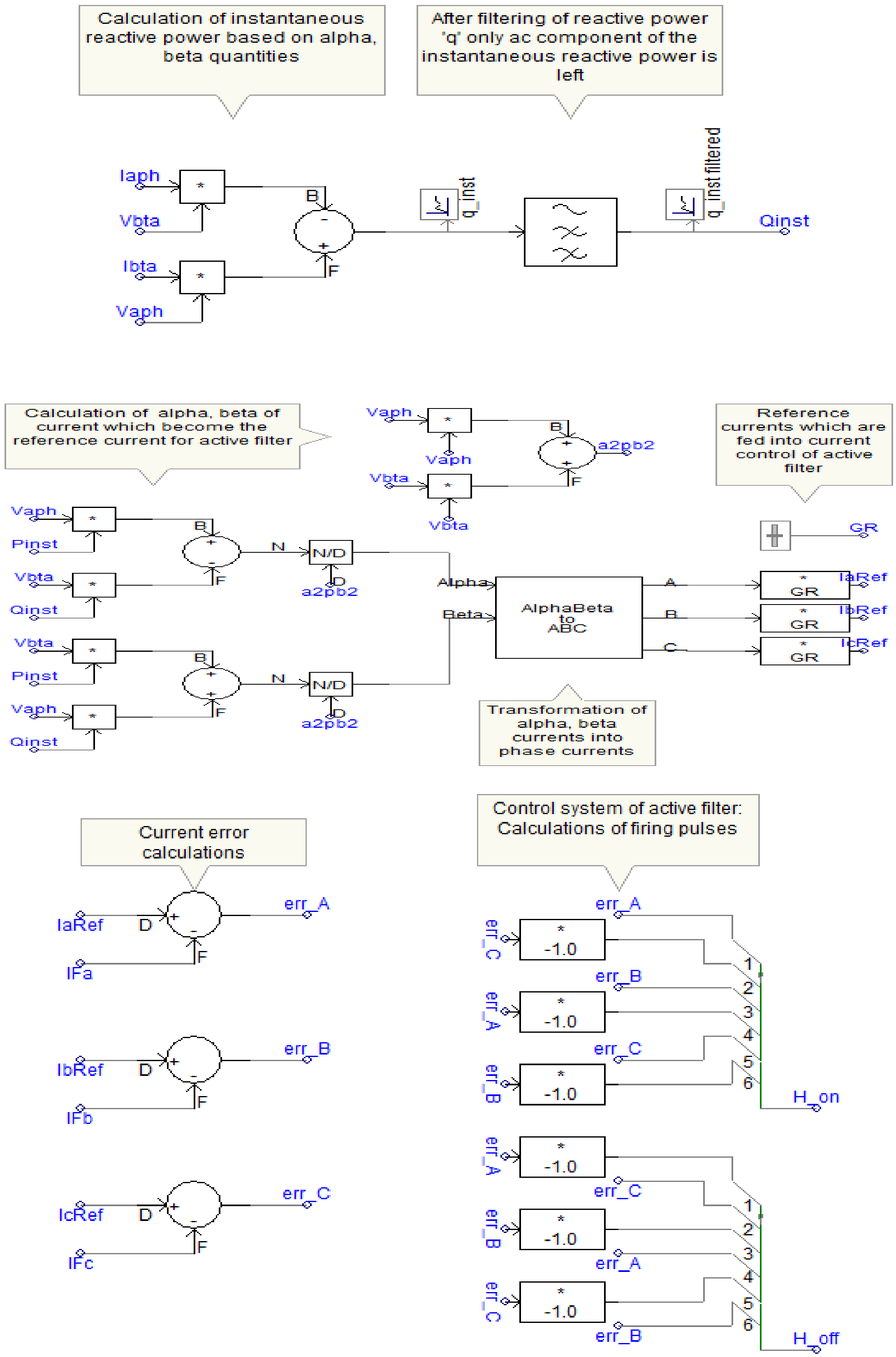
$$\begin{bmatrix} i_{shu} \\ i_{shv} \\ i_{shw} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad \text{........……………....} \quad (4.6)$$

The calculated harmonic current in each phase i_{sh}, is amplified by the gain K and input to a PWM controller as a voltage reference

$$V_C^* = K.i_{sh} \quad \text{…………………………………………...…….} \quad (4.7)$$

To produce PWM switching patterns, the PWM controller compares V_C^* with a triangle wave carrier.




Calculation of instantaneous reactive power based on alpha, beta quantities
After filtering of reactive power 'q' only ac component of the instantaneous reactive power is left
Iaph
Vbta
Ibta
Vaph
B
F
q_inst
q_inst filtered
Qinst
Calculation of alpha, beta of current which become the reference current for active filter
Vaph
Vbta
a2pb2
Reference currents which are fed into current control of active filter
GR
Pinst
Qinst
N
N/D
D
Alpha
Beta
AlphaBeta to ABC
A
B
C
IaRef
IbRef
IcRef
Transformation of alpha, beta currents into phase currents
Current error calculations
Control system of active filter: Calculations of firing pulses
IaRef
IFa
err_A
IbRef
IFb
err_B
IcRef
IFc
err_C
-1.0
H_on
H_off

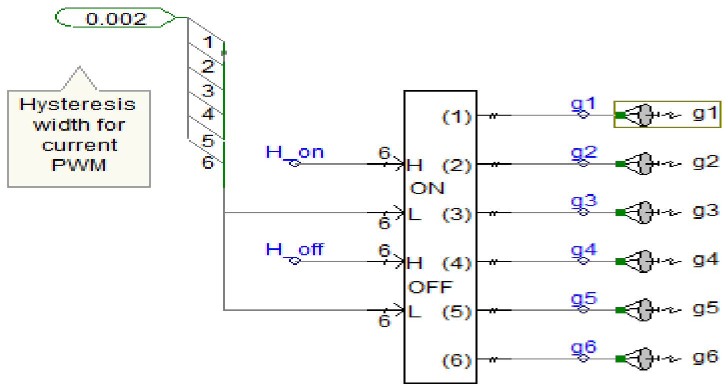
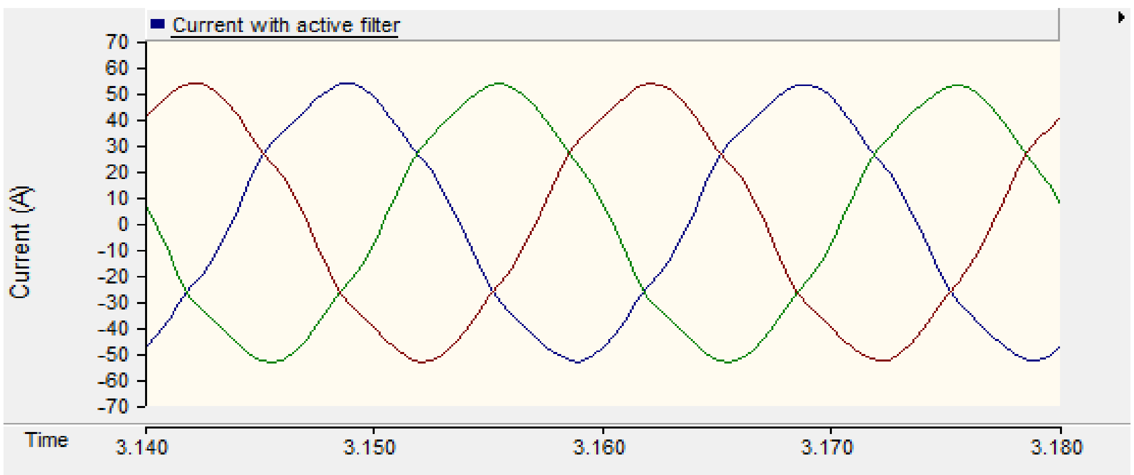
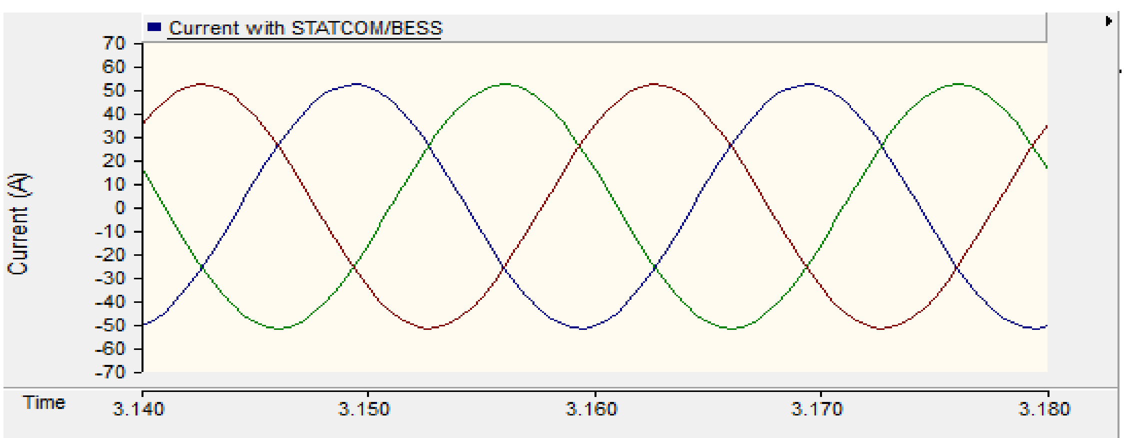


Figure 4.24: Control block of active filter.



(a)



(b)

Figure 4.25: Current waveform with (a) active filter and (b) STATCOM/BESS.

When the STATCOM/BESS is replaced by an active filter, then the active filter may reduce harmonics from the system but it cannot successfully eliminate harmonics to the extent as STATCOM/BESS does as shown in Fig. 4.25. The FFT analysis is done for measuring the current and voltage harmonic distortion. From the comparison shown in Fig. 4.26 and 4.27, it is proved that active filter is unable to extract the harmonic pollution from the system as effectively as STATCOM/BESS can. The voltage instability crisis is not minimized through active filter installation. It plays no role at removing voltage sag and swell problem as shown in Fig. 4.28.

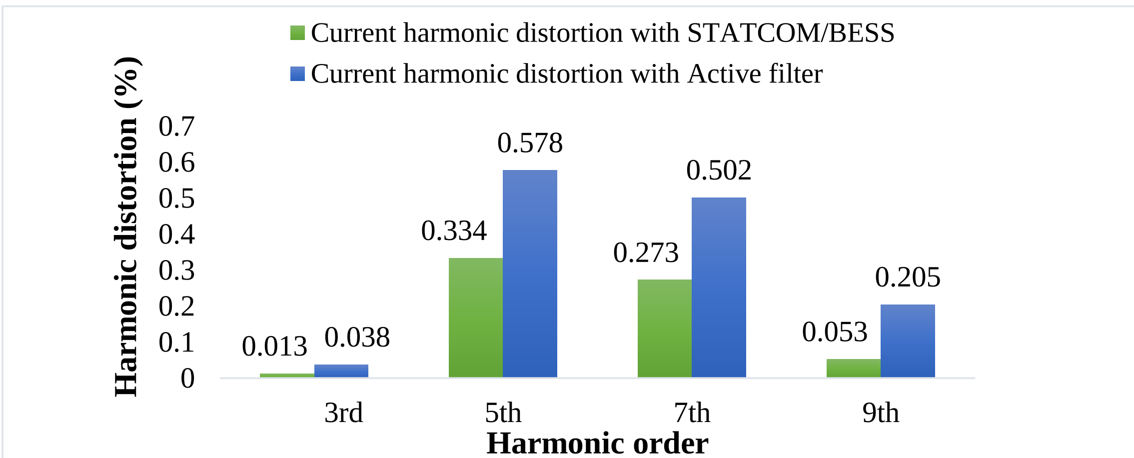


Figure 4.26: Comparison of individual current harmonic distortion (in %) between STATCOM/BESS and active filter.

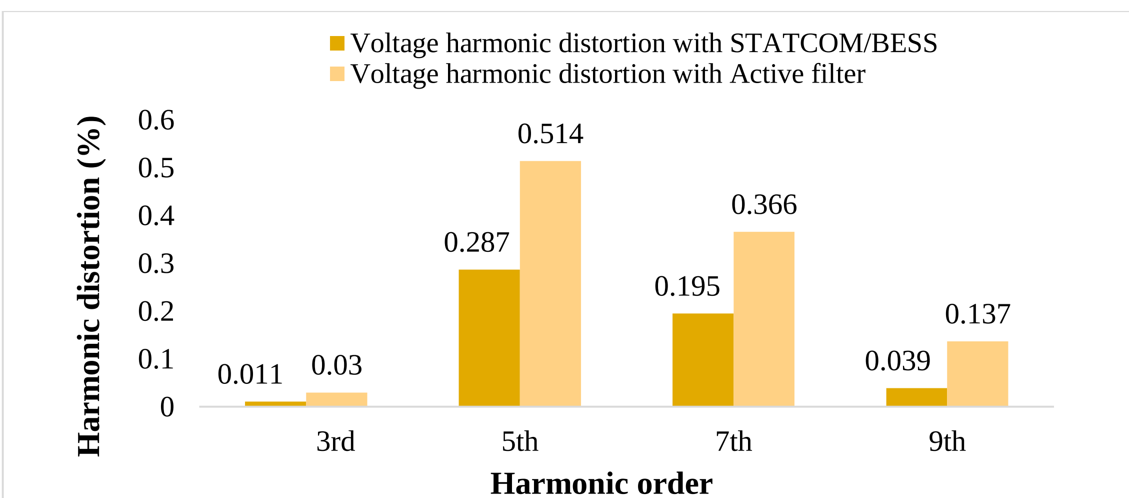


Figure 4.27: Comparison of individual voltage harmonic distortion (in %) between STATCOM/BESS and active filter.

STATCOM/BESS can minimize the voltage sag where as Active filter can not perform this but it has the capability to remove the harmonics. The comparison of the percentage of voltage sag during LLLG fault among without STATCOM/BESS, STATCOM/BESS and active filter is given in Table 4.3.

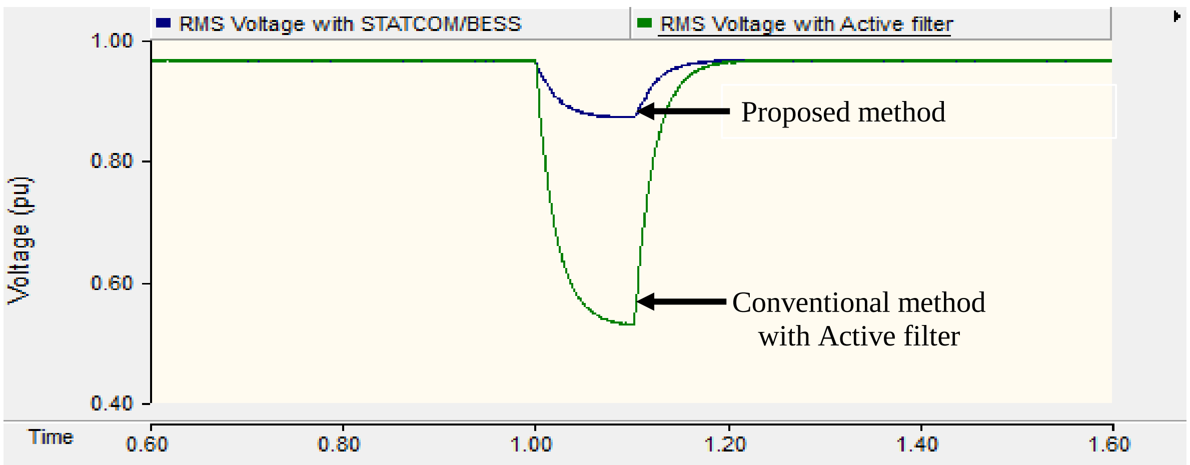


Figure 4.28: Comparison of voltage sag during LLLG fault between STACTCOM/BESS and active filter

Table 4.3: Comparison of voltage sag among, without STATCOM/BESS, STATCOM/BESS and active filter

Without STATCOM/BESS	With STATCOM/BESS	With active filter
53%	85%	54%

After analyzing different researches it is found that this model is more effective in case of harmonic reduction. The THD of current is analysis from different paper and a comparative study is given in Table 4.4.

Table 4.4: Comparison among proposed and other methods

Harmonic reduction technique	THD (%) before applying harmonic reduction technique	THD (%) after applying harmonic reduction technique
Current injection method [23]	38.95%	4.10%
Applying shunt active power filter [87]	25.74%	2.53%
By hybrid passive filter topology [77]	47.3%	1.1%
Applying supercapacitor based DSTATCOM [78]	20.66%	2.02%
Proposed method with RL load	**30.52%**	**0.56%**
Proposed method with induction motor with ASD load	**48.3%**	**0.84%**

From the above discussion, it is clear that in comparison with other methods, this proposed control method has superior quality by which it can effectively reduce the THD level.

4.6 Summary

The main aim of the research is to understand the non-liner load characteristics and find a solution to mitigate the power quality issues related to these non-linear loads. In this chapter, the evidences of the effectiveness of this model are given. The power quality problems and its solutions are given here and described all the finding with different case studies. Moreover, from the laboratory test, the THD of different type of loads are measured and understand clearly. From the analytical studies, it has been proved that the proposed control systems can successfully solve nearly all the power quality problems effectively.

CHAPTER V

Conclusion

5.1 Conclusion

People around the globe believe that the renewable energy will bring a positive change in the environment and the current practice of power generation. To promote the use of wind source worldwide, this research has focused to develop a wind based system with upgraded control mechanisms. This work is an important base, standing on which the world can go beyond the current horizon. This research is not only done for finding the solutions, but also it clearly identifies and tells about power quality problems precisely. In this research, a total setup of wind based DG is designed with effective control systems and then connected it to the DN and created a situation which is similar to the practical one under PSCAD/EMTDC environment. The power electronics converter which is a great source of harmonics is modeled with an upgraded current control mechanism with voltage dependent current limiter based on straight line theory which produces less harmonics in the system and for removing the maximum effects of harmonics a STATCOM/BESS is connected. The PWM technique is used for designing the voltage source converter of STATCOM/BESS and integration between these control mechanisms is done successfully. From critical studies on the theories, analysis of the developed model, it can be said that this thesis elaborates and clarifies the concepts and conditions regarding DG connected system with DN and it would help to solve problems associated with this system. The designed model is critically examined under some important load conditions and it is found with proper evidence that every load characteristics causes different level of harmonics within the system.

From this research, it is proved that the current harmonic, which is the most harmful harmonics, is reached to a higher level in case of induction motor whereas voltage harmonics is larger in arc furnace. In this system, it is found that 5^{th} and 7^{th} order harmonics are the prominent harmonics in this type of non-linear loads. For 5^{th} harmonic order, the current distortion is 33.40% and voltage distortion is 27.30% and after applying STATCOM/BESS the current and voltage distortion become 0.33% and 0.29% respectively. For 7^{th} harmonic order, the current and voltage harmonics are 27.80% and 21.85%, and after applying STATCOM/BESS they become 0.27% and 0.19% respectively. Before incorporating the STATCOM/ BESS, the THD of current was 48.3% and after applying that it becomes 0.84%. So, the designed system can reduce the THD up to 47.46%. Moreover, the power instability issue in the system is also mitigated by this proposed model.

The position and the number of DG play a crucial role in harmonics generation. The level of harmonic generation goes upward as the number of the DG gets increased. When the DG is connected with the non-linear load at the same bus the generated harmonics become the maximum and if the position of the DG shifts away from the non-linear load position the generated harmonics get reduced with distance.

However, the worst case may take place if the system faces any fault, which takes the generated harmonics at a drastic level, even may collapse any part of the system. Not only this, fault in the system causes voltage sag and it also creates a challenging situation for the total system. In case of LG fault, the proposed solution can reduce the voltage sag from 75% to 94% sag. And, at the time of LLG and LLLG faults, the system can reduce the voltage sag up to 32% and 30% respectively.

So, to conclude it can be boldly said that all research objectives are fulfilled by this research work perfectly whereas the STATCOM/BESS based DG system that is connected with DNs can successfully mitigate several power quality problems. To enhance the present power system by mitigating power quality issues, the designed model is an optimum solution to establish a greener world for the future generation.

5.2 Future Scope

This work can create the following scopes for future researchers:

- The proposed technology undoubtedly eradicates most of the power quality problems. In future the economic side will also be highlighted. More cost effective technologies can be developed by increasing researches on this topic so that wind based DG connected with DNs will be more popular at customer ends to move towards a sustainable world.

- Hybrid power system will be an addition of this research. Solar and hydro based power system will be designed with proper control mechanism and added to the wind system for generating more power with more diversity.

REFERENCES

1 N. A. Pambudi, K. Itaoka, N. Yamakawa and A. Kurosawa, “Future Japan power generation sector by introducing hydrogen plant with 80% CO2 emission reduction target: A preliminary analysis,” 2016 International Conference on Sustainable Energy Engineering and Application , Jakarta, 2016, pp. 66-69.

2 X. Peng, C. Qing, Y. Ye, Y. Deng, S. Ni, B. Xu, H. Yang, S. Chen, F. Cheng, D. Yu and J. Zhang, “Spatial and temporal effect on heavy metal pollution of atmospheric dust in fire coal of city power plant,” 2010 4th International Conference on Bioinformatics and Biomedical Engineering, Chengdu, 2010, pp. 1-4.

3 B. T. Jimenez, A. Alvear, A. AlYabes and A. Olaoye, “Technology Assessment and Selection of Renewable Energy Sources in the Galapagos Islands - Ecuador,” PICMET '07 - 2007 Portland International Conference on Management of Engineering & Technology, Portland, OR, 2007, pp. 2509-2529.

4 B. A. Radulescu and V. Radulescu, “Environmental solution with renewable to restore the capacity of the hydro-power lakes,” International Conference on Electromechanical and Power Systems, Iasi, 2017, pp. 233-238.

5 T. Agarwal, S. Verma and A. Gaurh, “Issues and challenges of wind energy,” International Conference on Electrical, Electronics, and Optimization Techniques, Chennai, 2016, pp. 67-72.

6 C. Veeramani and G. Mohan, “A fuzzy based pitch angle control for variable speed wind turbines,” International Journal of Engineering and Technology, India, vol. 5, no. 2, 2013.

7 M. R. Islam, S. Mekhilef and R. SaidurIslam, “Progress and recent trends of wind energy technology,” Renewable Sustainable Energy Reviews, vol.21, pp. 456-68, 2013.

8 A. M. Eltamaly, “Design and implementation of wind energy in Saudi Arabia,” Renewable Energy, vol.60, pp. 42-52, 2013.

9 S. S. Murthy, B. Singh, P. K. Goel and S. K. Tiwari, “A comparative study of fixed speed and variable speed wind energy conversion systems feeding the grid,” 7th International Conference on Power Electronics and Drive Systems, Bangkok, 2007, pp. 736-743.

10 M. R. R. Mojumdar, M. S. H. Himel, M. S. Rahman, and S. J. Hossain, "Electric machines & their comparative study for wind energy conversion systems, " Journal of Clean Energy Technologies, vol. 4, no. 4, Jul. 2016.

11 S. Bhowmik and R. Spee, “Wind speed estimation based variable speed wind power generation,” Industrial Electronics Society, 1998, Proceedings of the 24th Annual Conference of the IEEE, Aachen, 1998, pp. 596-601 vol.2.

12 V. Yaramasu, A. Dekka, M. J. Duran, S. Kouro and B. Wu, "PMSG-based wind energy conversion systems: survey on power converters and controls," IET Electric Power Applications, vol. 11, no. 6, pp. 956-968, 2017.

13 E. Hamatwi, M. N. Gitau and I. E. Davidson, "Control of a direct-driven permanent magnet synchronous generator-based wind turbine to achieve maximum wind-power extraction," IEEE PES PowerAfrica, Accra, 2017, pp. 65-74.

14 S. Jahdi, A. Etemadian and L. L. Lai, "Voltage profile stability analysis of radial distribution power systems in presence of DGs," 11th International Conference on Electrical Power Quality and Utilisation, Lisbon, 2011, pp. 1-6.

15 S. M. M. Larimi and M. R. Haghifam, "DG allocation based on modified nodal price with consideration of loss and reliability using PSO," 22nd International Conference and Exhibition on Electricity Distribution, Stockholm, 2013, pp. 1-4.

16 M. J. H. Rawa, D. W. P. Thomas and M. Sumner, "Simulation of non-linear loads for harmonic studies," 11th International Conference on Electrical Power Quality and Utilisation, Lisbon, 2011, pp. 1-6.

17 W. Su, Z. Li and Z. Shao, "The harmonic calculation model of non-linear load," 2014 China International Conference on Electricity Distribution, Shenzhen, 2014, pp. 866-872.

18 K. C. Umeh, A. Mohamed and R. Mohamed, "Determining harmonic characteristics of typical single phase non-linear loads," Research and Development SCORED 2003, Proceedings, Student Conference on Proceedings, Malaysia, 2003, pp. 413-419.

19 C. Venkatesh, D. Srikanth Kumar, "Modelling of nonlinear loads and estimation of harmonics in industrial distribution system," Fifteenth National Power Systems Conference, IIT Bombay, December 2008.

20 L. Alhafadhi, J. Asumadu, and A. Alsafi, "Total harmonics distortion reduction using adaptive, Weiner, and Kalman filters," IEEE 7th Annual Computing and Communication Workshop and Conference, Las Vegas, 2017, pp. 1-8.

21 T. Tadivaka, M. Srikanth, and T. V. Muni, "THD reduction and voltage flicker mitigation in power system based on STATCOM," International Conference on Information Communication and Embedded Systems, Chennai, 2014, pp. 1-6.

22 O. Hemakesavulu, M. S. Sandeep, and C. S. Durganjali, "Ann controller for harmonic reduction in grid connected system," International Conference on Communication and Electronics Systems, Coimbatore, 2016, pp. 1-6.

23 A. H. Samra and A. Tesome, "Current injection method to eliminate harmonics in an AC power system," Conference Record Industrial and Commercial Power Systems Technical Conference, USA, 1993, pp. 85-91.

24 Arena, What is renewable energy? [Online] Availability: http://arena.gov.au/about-renewable-energy/ (access date: March, 2017)

25 World Energy Resources 2016, 24th Edition, WEC, UK, October, 2016.

26 A. Macintosh and C. Downie, “Wind farms the facts and the fallacies,” The Australia Institute, Rep. 91, 2006.

27 G. Leventhall, “Infrasound from wind turbines – fact, fiction or deception,” Canadian Acoustics, vol. 34 no.2, 2006.

28 P. C. Sai, R. S. Yadav, R. N. Raj and G. R. K. Gupta, “Design and simulation of high efficiency counter-rotating vertical axis wind turbine arrays,” 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development , Pattaya, 2014, pp. 1-9.

29 M. Sharma, B. Rieger, C. Jou and B. Butka, “Development of helical vertical axis wind turbine,” 2012 Proceedings of IEEE Southeastcon, Orlando, FL, 2012, pp. 1-5.

30 W. Hu, Y. Wang, X. Song and Z. Wang, “Development of vertical-axis wind turbine with asynchronous generator interconnected to the electric network,” 2008 International Conference on Electrical Machines and Systems, Wuhan, 2008, pp. 2289-2293.

31 T. Dang, “Introduction, history, and theory of wind power,” 41st North American Power Symposium, Starkville, MS, USA, 2009, pp. 1-6.

32 M. R. Islam, Y. G. Guo, and J. G. Zhu, “A review of offshore wind turbine nacelle: Technical challenges, and research and development trends,” Renewable and Sustainable Energy Reviews, vol. 33, pp. 161-176, 2014.

33 V. Yaramasu and B. Wu, B, Model predictive control of wind energy conversion systems, Wiley-IEEE Press, Hoboken, NJ, 2016.

34 A BTM wind report: world wind energy market update, Navigent, 2016.

35 H. Polinder, J. A. Ferreira, B. B. Jensen, A. B. Abrahamsen, K. Atallah and R. A. McMahon, “Trends in Wind Turbine Generator Systems,” in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 3, pp. 174-185, 2013.

36 B. Wu, N. Zargari, S. Kouro, and Y. Lang, Power Conversion and Control of Wind Energy Systems, Wiley-IEEE Press, Hoboken, NJ, 2011.

37 E. Levi, “Multiphase electric machines for variable-speed applications,” in IEEE Transactions on Industrial Electronics, vol. 55, no. 5, pp. 1893-1909, 2008.

38 J. A. Baroudi, V. Dinavahi and A. M. Knight, “A review of power converter topologies for wind generators,” IEEE International Conference on Electric Machines and Drives, San Antonio, TX, 2005, pp. 458-465.

39 Z. Chen and E. Spooner, “Current source thyristor inverter and its active compensation system,” in IEE Proceedings - Generation, Transmission and Distribution, vol. 150, no. 4, pp. 447-454, 2003.

40 P. Tenca, A. A. Rockhill and T. A. Lipo, "Wind turbine current-source converter providing reactive power control and reduced harmonics," in IEEE Transactions on Industry Applications, vol. 43, no. 4, pp. 1050-1060, 2007.

41 P. Tenca, A. A. Rockhill, T. A. Lipo and P. Tricoli, "Current source topology for wind turbines with decreased mains current harmonics, further reducible via functional minimization," in IEEE Transactions on Power Electronics, vol. 23, no. 3, pp. 1143-1155, 2008.

42 M. Chinchilla, S. Arnaltes and J.C. Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid," IEEE Transations on Energy Conversion, vol. 21, issue 1, pp.130-135, 2006.

43 A. Uehara, A. Pratap, T. Goya, T. Senjyu, A. Yona, N. Urasaki and T. Funabashi, "A coordinated control method to smooth wind power fluctuations of a PMSG-Based WECS," IEEE Transactions on Energy Conversion, Vol. 26, No. 2, pp. 550-558, 2011.

44 K. Nishida, T. Ahmed, M. Nakaoka, "A cost-effective high-efficiency power conditioner with simple MPPT control algorithm for wind-power grid integration," IEEE Transactions on Industry Applications, vol. 47, no. 2, pp. 893-900, 2011.

45 Y. Xia, H. K. Ahmed, B. W. Williams, "A new maximum power point tracking technique for permanent magnet synchronous generator based wind energy conversion system," IEEE Transactions on Power Electronics, vol. 26, no. 1, pp. 3609-3620, 2011.

46 H. Zhang, L. M. Tolbert, "Efficiency impact of silicon carbide power electronics for modern wind turbine full scale frequency converter," IEEE Transaction on Industrial Electronics, vol. 58, no. 1, pp. 21, 2011.

47 J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," IEEE Transactions on Industrial Electronics, vol. 54, no. 6, pp. 2930–2945, 2007.

48 J. Rodriguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: a survey of topologies, controls, and applications," IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 724–738, 2002.

49 J. Li, Y. Zhu, H. Xu and H. Xu, "CPS-SPWM flying capacitor three-level back-to-back converter applicative direct-drive wind power generator system," 2009 International Conference on Sustainable Power Generation and Supply, Nanjing, 2009, pp. 1-6.

50 C. Xia, X. Gu, T. Shi, and Y. Yan, "Neutral-point potential balancing of three-level inverters in direct-driven wind energy conversion system," IEEE Transactions on Energy conversion, vol. 26, no. 1, pp. 18-29, 2011.

51 H. N. G. Chong, M. A. Parker, L. Ran, P. J. Tavner, J. R. Bumby and E. Spooner, "A multilevel modular converter for a large, light weight wind turbine generator," IEEE Transactions on Power Electronics, vol. 23, no. 3, pp. 1062-1074, 2008.

52 A. Garces and M. Molinas, "A study of efficiency in a reduced matrix converter for offshore wind farms," IEEE Transaction on Industrial Electronics, vol. 59, no. 1, pp. 184-193, 2012.

53 S.M. Dehghan, M. Mohamadian, A.Y. Varjani, “A new variable-speed wind energy conversion system using permanent-magnet synchronous enerator and Z source inverter,” IEEE Transactions on Energy Conversions, vol. 24, no. 3, pp 714-724, 2009.

54 A. F. A. Kadir, A. Mohamed and H. Shareef, “Harmonic impact of different distributed generation units on low voltage distribution system,” 2011 IEEE International Electric Machines & Drives Conference, Niagara Falls, ON, 2011, pp. 1201-1206.

55 M. Dixit, P. Kundu and H. R. Jariwala, “Optimal placement and sizing of DG in distribution system using artificial bee colony algorithm,” IEEE 6th International Conference on Power Systems, New Delhi, 2016, pp. 1-6.

56 A. Parizad, A. Khazali and M. Kalantar, “Optimal placement of distributed generation with sensitivity factors considering voltage stability and losses indices,” 18th Iranian Conference on Electrical Engineering, Isfahan, Iran, 2010, pp. 848-855.

57 G. M. Shafiullah and A. M. T. Oo, “Analysis of harmonics with renewable energy integration into the distribution network,” IEEE Innovative Smart Grid Technologies - Asia, Bangkok, 2015, pp. 1-6.

58 S. Sumathi, L. A. Kumar and P. Surekha, Harmonic reduction Techniques in renewable energy systems, Springer, 2015.

59 N. Shah, “Harmonics in power systems causes, effects and control,” Siemens, USA, 2013, pp.1-24.

60 J. C. Das, Power system analysis: short-circuit load flow and harmonics, Marcel Dekker, 2002.

61 M. J. H. Rawa, D. W. P. Thomas and M. Sumner, “Simulation of non-linear loads for harmonic studies,” 11th International Conference on Electrical Power Quality and Utilisation, Lisbon, 2011, pp. 1-6.

62 S. S. H. Bukhari, S. Atiq and B. I. Kwon, “An inrush current elimination technique for a voltage sag compensator while powering transformer-coupled loads,” IEEE Energy Conversion Congress and Exposition, Montreal, QC, 2015, pp. 2710-2714.

63 M. A. Bhaskar, S. S. Dash, C. Subramani, M. J. Kumar, P. R. Giresh and M. V. Kumar, "Voltage quality improvement using DVR," International Conference on Recent Trends in Information, Telecommunication and Computing, Kochi, Kerala, 2010, pp. 378-380.

64 P. K. Dash, D.P. Swain, A. C. Liew and S. Raman, “An adaptive linear combiner for on-line tracking of power system harmonics,” IEEE Transactions on Power Systems, vol. 11, no.4, pp.1730-1736, 1996.

65 A. V. Ital and S. A. Borakhade, “Compensation of voltage sags and swells by using Dynamic Voltage Restorer (DVR),” International Conference on Electrical, Electronics, and Optimization Techniques, Chennai, 2016, pp. 1515-1519.

66 A. A. Hussein, M. H. Ali, “Comparison between DVR and SFCL for fault ride through capability improvement of fixed speed wind generator,” IEEE transaction 2014.

67 N. Mithulananthan, C.A. Canizares, J. Reeve and G. J. Rogers, “Comparison of PSS, SVC and STATCOM Controllers for Damping Power System Oscillations,” IEEE Transactions on Power Systems, vol. 18(2), pp. 786-792, 2003.

68 A. D. D. Rosso, C. A. Canizares and V. M. Dona, “A study of TCSC controller design for power system stability improvement,” IEEE Transactions on Power Systems, vol. 18(4), pp. 1487-1496, 2003.

69 M. S. ElMoursi and A. M. Sharaf, “Voltage stabilization and reactive compensation using a novel FACTS STATCOM scheme,” Canadian Conference on Electrical and Computer Engineering, Saskatoon, 2005, pp. 537-540.

70 S. T. Chavhan, C. L. Bhattar, P. V. Koli and V. S. Rathod, “Application of STATCOM for power quality improvement of grid integrated wind mill,” IEEE 9th International Conference on Intelligent Systems and Control, Coimbatore, 2015, pp. 1-7.

71 S. K. George and F. M. Chacko, “Comparison of different control strategies of STATCOM for power quality improvement of grid connected wind energy system," 2013 International Mutli-Conference on Automation, Computing, Communication, Control and Compressed Sensing, Kottayam, 2013, pp. 650-655.

72 J. Castaneda, J. Enslin, D. Elizondo, N. Abed and S. Teleke, “Application of STATCOM with energy storage for wind farm integration,” IEEE PES Transmission and Distribution Conference and Exposition, 2010, New Orleans, LA, USA, 2010, pp. 1-6.

73 W. B. Lawrance, G. Michalik, W. Mielczarski and J. Szczepanik, “Reduction of harmonic pollution in distribution networks,” Energy Management and Power Delivery, Proceedings of EMPD '95., 1995 International Conference on, 1995, pp. 198-202 vol.1.

74 M. Hassanzadeh, A. Sheikholeslami, H. Ghoreishi, S. Mohseni and M. Nazari, “A novel method for current harmonic reduction of CFLs in large number usage,” The 6th Power Electronics, Drive Systems & Technologies Conference, Tehran, 2015, pp. 424-429.

75 H. Lou, C. Mao, D. Wang, J. Lu and L. Wang, “Fundamental modulation strategy with selective harmonic elimination for multilevel inverters,” in IET Power Electronics, vol. 7, no. 8, pp. 2173-2181, 2014.

76 S. J. Huang, J. C. Wu, “Design and operation of cascaded active power filters for the reduction of harmonic distortions in a power system,” IEEE Proceedings of Generation, Transmission and Distribution, pp. 193–9, 1999.

77 A. Hamadi, S. Rahmani and K. Al-Haddad, “A hybrid passive filter configuration for VAR control and harmonic compensation,” in IEEE Transactions on Industrial Electronics, vol. 57, no. 7, pp. 2419-2434, 2010.

78 M. Mangaraj, A. K. Panda and T. Penthia, "Supercapacitor supported DSTATCOM for harmonic reduction and power factor correction," IEEE Students' Conference on Electrical, Electronics and Computer Science, Bhopal, 2016, pp. 1-6.

79 D. Das, H. S. Nagi, and D. P. Kothari, "Novel method for solving radial distribution networks," IEE Proceedings - Generation, Transmission and Distribution, vol. 141, no. 4, pp. 291-298, 1994.

80 X. Liang and Y. Luy, "Harmonic analysis for induction motors," Canadian Conference on Electrical and Computer Engineering, Ottawa, Ont., 2006, pp. 172-177.

81 P. Chittora, A. Singh, and M. Singh, "Modeling and analysis of power quality problems in electric arc furnace," Annual IEEE India Conference, New Delhi, 2015, pp. 1-6.

82 E. Acha, A. Semlyen, and N. Rajakovic, "A harmonic domain computational package for nonlinear problems and its application to electric arcs," IEEE Transactions on Power Delivery, vol. 5, no. 3, pp. 1390-1397, 1990.

83 "IEEE recommended practices and requirements for harmonic control in electrical power systems," in IEEE Std 519-1992, pp.1-112, 1993.

84 M. H. Bollen, Understanding power quality problems: voltage sags and interruptions. USA: Wiley-IEEE Press, 1999.

85 R. Sedaghati, N. M. Afroozi, Y. Nemati, A. Rohani, A. R. Toorani, N. Javidtash, A. Heydarzadegan, and H. Sedaghati, " A survey of voltage sags and voltage swells phenomena in power quality problems," International Journal of Scientific Research and Management , vol. 1, no. 9, pp. 458-462, 2013.

86 H. Fujita and H. Akagi, "A practical approach to harmonic compensation in power systems - series connection of passive and active filters," IEEE Transactions on Industry applications, vol. 27, no. 6, pp. 1020-1025, 1991.

87 S. Samal, P. K. Hota and P. K. Barik, "Harmonics mitigation by using shunt active power filter under different load condition," International Conference on Signal Processing, Communication, Power and Embedded System, Paralakhemundi, 2016, pp. 94-98.

APPENDIX A

Table A.1: Specifications of the model

Wind Turbine	**Specification**
Generator rating MVA	3 [MVA]
Machine rated angular mechanical speed	3.14 [rad/s]
Rotor radius	46.2 [m]
Rotor area	6716 [m^2]
Air density	1.225 [kg/m^3]
Gear box efficiency	1 [pu]
Wind Governor	**Specification**
Rated angular frequency of the machine	3.1416 [rad/s]
Turbine rated power	3 [MW]
Machine rated power	3 [MVA]
Governor type	MOD 2
Initial pitch angle	0 [deg]
PMSG Machine	**Specification**
Rated RMS line to neutral voltage	0.69 [kV]
Rated RMS line current	1.45 [kA]
Base angular frequency	314.16 [rad/s]
Inertia constant	6.3 [s]
Neutral series resistance	20 [pu]
Iron loss resistance	30 [pu]
No. of Q axis damper winding	1
Mechanical friction and windage	0.02 [pu]
6 Pulse Bridge of AC/DC/AC Converter	**Specification**
Rated frequency	50 [Hz]
Proportional gain	10

Integral gain	100
Thyristor ON resistance	0.01 [ohm]
Thyristor OFF resistance	1.0E6 [ohm]
Breakover voltage	1.0E6 [kV]
Snubber capacitance	0.05 [uF]
Snubber resistance	5000 [ohm]
Voltage Dependent Current Limits	**Specification**
Volts for applying limit	1.52 [pu]
Volts for removing limit	1.68 [pu]
Lag time constant	0.0002 [s]
Current limit	0.06 [pu]
Current Controller of AC/DC/AC Converter	**Specification**
Current margin	0.01 [pu]
Slope of current error	0.1 [pu]
Alpha maximum limit	3.142 [r]
Alpha minimum limit	0.0 [r]
Integral gain	5.0
Proportional gain	0.02
STATCOM/BESS	**Specification**
Base frequency	50 [Hz]
Proportional gain	50
Integral gain	500
Modulo factor	360
Lead time constant	0.007 [s]
Lag time constant	0.0001[s]

APPENDIX B

B. 1 Code of PMSG based Wind Turbine

```
SUBROUTINE DSDyn()

!---------------------------------------
! Standard includes
!---------------------------------------

      INCLUDE 'nd.h'
      INCLUDE 'emtconst.h'
      INCLUDE 'emtstor.h'
      INCLUDE 's0.h'
      INCLUDE 's1.h'
      INCLUDE 's2.h'
      INCLUDE 's4.h'
      INCLUDE 'branches.h'
      INCLUDE 'pscadv3


.h'
      INCLUDE 'fnames.h'
      INCLUDE 'radiolinks.h'
      INCLUDE 'matlab.h'

!---------------------------------------
! Function/Subroutine Declarations
!---------------------------------------

!     SUBR    WINDSRC       ! Wind speed
model
      REAL    LIMIT         ! Hard Limiter
!     SUBR    WINDGOV       ! Wind Governor
model
!     SUBR    WINDTURB      ! Wind turbine
model
!     SUBR    NEWSNC        ! Synchronous
Machine Simulation
      REAL    VM3PH2        ! 3 Phase
Voltmeter

!---------------------------------------
! Variable Declarations
!---------------------------------------


! Subroutine Parameters

! Electrical Node Indexes
      INTEGER NT_1(3)

! Control Signals
      INTEGER InitGv, InitEx
      REAL    RT_1, RT_2, RT_3, RT_4, RT_5,
W
      REAL    Pgene, Qgene, Testdy, I(3),
V(3)
      REAL    RT_6, RT_7, RT_8, RT_9, RT_10
      REAL    RT_11, RT_12, RT_13, RT_14

! Internal Variables
      INTEGER SP_TQ, M_ACTV
      REAL    Pw_O, Qva_O, Vn_O, Cn_O,
LdA_O
      REAL    Tht_O, Tesd_O, Tmsd_O, Z_O1,
Z_O2
      REAL    Z_O3, Z_O4, Z_O5, Z_O6, SP_IN

! Indexing variables
      INTEGER ISTOI, ISTOF, IT_0
! Storage Indexes
      INTEGER IPGB
! Control/Monitoring
      INTEGER ISUBS, SS(1), IBRCH(1), INODE
! SS/Node/Branch/Xfmr
!---------------------------------------
! Record local indexes
!---------------------------------------

! Dsdyn <-> Dsout transfer index storage
      NTXFR = NTXFR + 1
      TXFR(NTXFR,1) = NSTOL
      TXFR(NTXFR,2) = NSTOI
      TXFR(NTXFR,3) = NSTOF

! Record Offset and Increment Storage
Counters
      ISTOI     = NSTOI
      NSTOI     = NSTOI + 2
      ISTOF     = NSTOF
      NSTOF     = NSTOF + 24
      IPGB      = NPGB
      NPGB      = NPGB + 13
      INODE     = NNODE + 2
      NNODE     = NNODE + 5

! Initialize Subsystem Mapping

      ISUBS = NSUBS + 0
      NSUBS = NSUBS + 1

      DO 100  IT_0 = 1,1
         SS(IT_0) = SUBS(ISUBS + IT_0)
  100 CONTINUE

! Initialize Branch Mapping.

      IBRCH(1)     = NBRCH(SS(1))
      NBRCH(SS(1)) = NBRCH(SS(1)) + 3

!---------------------------------------
! Transfers from storage arrays
!---------------------------------------

      RT_1     = STOF(ISTOF + 1)
      RT_2     = STOF(ISTOF + 2)
      RT_3     = STOF(ISTOF + 3)
```

```
      RT_4      = STOF(ISTOF + 4)
      RT_5      = STOF(ISTOF + 5)
      W         = STOF(ISTOF + 6)
      Pgene     = STOF(ISTOF + 7)
      Qgene     = STOF(ISTOF + 8)
      Testdy    = STOF(ISTOF + 9)
      RT_6      = STOF(ISTOF + 16)
      RT_7      = STOF(ISTOF + 17)
      RT_8      = STOF(ISTOF + 18)
      RT_9      = STOF(ISTOF + 19)
      RT_10     = STOF(ISTOF + 20)
      RT_11     = STOF(ISTOF + 21)
      RT_12     = STOF(ISTOF + 22)
      RT_13     = STOF(ISTOF + 23)
      RT_14     = STOF(ISTOF + 24)
      InitGv    = STOI(ISTOI + 1)
      InitEx    = STOI(ISTOI + 2)

! Array(1:3) quantities...
      DO 101  IT_0 = 1,3
         I(IT_0) = STOF(ISTOF + 9 + IT_0)
         V(IT_0) = STOF(ISTOF + 12 + IT_0)
  101 CONTINUE

!---------------------------------------
! Transfer from Imports
!---------------------------------------


!---------------------------------------
! Electrical Node Lookup
!---------------------------------------


! Array(1:3) quantities...
      DO 102  IT_0 = 1,3
         NT_1(IT_0) = NODE(INODE + 0 +
IT_0)
  102 CONTINUE

!---------------------------------------
! Read Model data (if any)
!---------------------------------------

      IF ( TIMEZERO ) THEN
         FILENAME = 'Main.dta'
         CALL EMTDC_OPENFILE
         SECTION = 'DATADSD:'
         CALL EMTDC_GOTOSECTION
      ENDIF

!---------------------------------------
! Generated code from module definition
!---------------------------------------


! 10:[const] Real Constant
      RT_9 = 1.0

! 50:[wind_source] Wind Source
!
      CALL WINDSRC(13.0,1.0,1.0,
RT_14,RT_13)

! 60:[hardlimit] Hard Limiter
!  Hard_Limit
      RT_12 = LIMIT(4.0, 25.0, RT_13)
!

! 80:[pgb] Output Channel 'Wind speed'

      PGB(IPGB+7) = RT_12

! 90:[const] Real Constant
      RT_11 = 314.16

! 100:[const] Real Constant 'D'
      RT_10 = 100.0

! 110:[mult] Multiplier
!
      RT_4 = W * RT_11
!

! 120:[div] Divider
!
      IF (ABS(RT_10) .LT. 1.0E-10) THEN
         IF (RT_10 .LT. 0.0)  THEN
            RT_3 = -1.0E10 * RT_4
         ELSE
            RT_3 =  1.0E10 * RT_4
         ENDIF
      ELSE
         RT_3 = RT_4 / RT_10
      ENDIF
!

! 130:[wind_governor] Wind Turbine Governor
      CALL
WINDGOV(RT_3,RT_2,0.277777777778*3,1.0,3.14
16,RT_5)

! 140:[wind_turbine] Wind Turbine
      CALL
WINDTURB(RT_12,RT_3,RT_5,1.0,RT_1,RT_2)

! 150:[sync_machine] Synchronous Machine
'Sync1'
!  Synchronous machine model
      STORI(NSTORI) = NINT(STOR(NEXC+294))
      SP_IN = 7.9
      CALL NEWSNC(SS(1),
NT_1(1),NT_1(2),NT_1(3),0.0,0.69,0.0,0,1,1.
0,0,&

&1,SP_IN,RT_1,0,0,1.0,0.0,7.9,RT_9,0,1.0,RT
_8,Vn_O,Cn_O,LdA_O,Tht_O&

&,W,RT_6,Pw_O,Qva_O,Tmsd_O,Tesd_O,M_ACTV,SP
_TQ,1,Z_O1,1,Z_O2,1,Z_O3&
     &,1,Z_O4,1,Z_O5,1,Z_O6,0)
      RT_7 = RT_1
!     IF (SP_TQ .EQ. 0) RT_7 = STOR(NEXC-
375+22)+STOR(NEXC-375+347)
      IF (SP_TQ .EQ. 0) RT_7 = Tmsd_O
      IF ((M_ACTV .EQ. 1) .AND.
(STORI(NSTORI).EQ.0)) THEN
          IF (STOR(NEXC-375+293).GT.0.5)
THEN
              STORF(NSTORF) = STOR(NEXC-
375+161)
          ELSE
              STORF(NSTORF) = STOR(NEXC-
375+296)
          ENDIF
      ENDIF
      IF (M_ACTV .EQ. 1) THEN
        STORF(NSTORF+1) = STORF(NSTORF+1) +
(W-7.9)*DELT
```

```
        IF (SP_TQ .EQ. 0) STORF(NSTORF+2) =
LdA_O
        STORF(NSTORF+3) = STORF(NSTORF) +
STORF(NSTORF+1) + STORF(NSTORF&
     &+2)
      ELSE
        STORF(NSTORF+3) = 0.0
      ENDIF


      W = W/7.9
      Pgene = Pw_O/3.0015
      Qgene = Qva_O/3.0015
      Testdy = Tesd_O
      InitGv = SP_TQ
      InitEx = M_ACTV
      NSTORF = NSTORF + 4
      NSTORI = NSTORI + 1
!  End of code for Synchronous machine
model
!

! 160:[pgb] Output Channel 'Pt'

      PGB(IPGB+8) = 3.0 * RT_2

! 170:[pgb] Output Channel 'Wm'

      PGB(IPGB+9) = RT_3

! 180:[pgb] Output Channel 'Tm'

      PGB(IPGB+10) = 955000.0 * RT_1

! 190:[pgb] Output Channel 'Tg'

      PGB(IPGB+11) = 2.8 * Testdy

! 200:[pgb] Output Channel 'Reactive power'

      PGB(IPGB+12) = 3.0 * Qgene

! 210:[pgb] Output Channel 'Active power'

      PGB(IPGB+13) = 3.0 * Pgene

!---------------------------------------
! Feedbacks and transfers to storage
!---------------------------------------

      STOF(ISTOF + 1) = RT_1
      STOF(ISTOF + 2) = RT_2
      STOF(ISTOF + 3) = RT_3
      STOF(ISTOF + 4) = RT_4
      STOF(ISTOF + 5) = RT_5
      STOF(ISTOF + 6) = W
      STOF(ISTOF + 7) = Pgene
      STOF(ISTOF + 8) = Qgene
      STOF(ISTOF + 9) = Testdy
      STOF(ISTOF + 16) = RT_6
      STOF(ISTOF + 17) = RT_7
      STOF(ISTOF + 18) = RT_8
      STOF(ISTOF + 19) = RT_9
      STOF(ISTOF + 20) = RT_10
      STOF(ISTOF + 21) = RT_11
      STOF(ISTOF + 22) = RT_12
      STOF(ISTOF + 23) = RT_13
      STOF(ISTOF + 24) = RT_14
      STOI(ISTOI + 1) = InitGv
      STOI(ISTOI + 2) = InitEx

! Array(1:3) quantities...
      DO 103  IT_0 = 1,3
         STOF(ISTOF + 9 + IT_0) = I(IT_0)
         STOF(ISTOF + 12 + IT_0) = V(IT_0)
  103 CONTINUE

!---------------------------------------
! Transfer to Exports
!---------------------------------------

!---------------------------------------
! Close Model Data read
!---------------------------------------

      IF ( TIMEZERO ) CALL EMTDC_CLOSEFILE
      RETURN
      END

!==========================================
=============================

      SUBROUTINE DSOut()

!---------------------------------------
! Standard includes
!---------------------------------------

      INCLUDE 'nd.h'
      INCLUDE 'emtconst.h'
      INCLUDE 'emtstor.h'
      INCLUDE 's0.h'
      INCLUDE 's1.h'
      INCLUDE 's2.h'
      INCLUDE 's4.h'
      INCLUDE 'branches.h'
      INCLUDE 'pscadv3.h'
      INCLUDE 'fnames.h'
      INCLUDE 'radiolinks.h'
      INCLUDE 'matlab.h'

!---------------------------------------
! Function/Subroutine Declarations
!---------------------------------------

      REAL    EMTDC_VVDC    !

!---------------------------------------
! Variable Declarations
!---------------------------------------


! Electrical Node Indexes
      INTEGER NT_1(3)

! Control Signals
      REAL    I(3), V(3)

! Internal Variables
      INTEGER IVD1_1

! Indexing variables
      INTEGER ISTOL, ISTOI, ISTOF, IT_0
! Storage Indexes
      INTEGER IPGB
! Control/Monitoring
      INTEGER ISUBS, SS(1), IBRCH(1), INODE
! SS/Node/Branch/Xfmr
```

```
!--------------------------------------
! Record local indexes
!--------------------------------------

! Dsdyn <-> Dsout transfer index storage
      NTXFR = NTXFR + 1
      ISTOL = TXFR(NTXFR,1)
      ISTOI = TXFR(NTXFR,2)
      ISTOF = TXFR(NTXFR,3)

! Record Offset and Increment Storage
Counters
      IPGB      = NPGB
      NPGB      = NPGB + 13
      INODE     = NNODE + 2
      NNODE     = NNODE + 5

! Initialize Subsystem Mapping

      ISUBS = NSUBS + 0
      NSUBS = NSUBS + 1

      DO 100  IT_0 = 1,1
         SS(IT_0) = SUBS(ISUBS + IT_0)
  100 CONTINUE

! Initialize Branch Mapping.

      IBRCH(1)     = NBRCH(SS(1))
      NBRCH(SS(1)) = NBRCH(SS(1)) + 3

!--------------------------------------
! Transfers from storage arrays
!--------------------------------------


! Array(1:3) quantities...
      DO 101  IT_0 = 1,3
         I(IT_0) = STOF(ISTOF + 9 + IT_0)
         V(IT_0) = STOF(ISTOF + 12 + IT_0)
  101 CONTINUE

!--------------------------------------
! Electrical Node Lookup
!--------------------------------------


! Array(1:3) quantities...
      DO 102  IT_0 = 1,3
         NT_1(IT_0) = NODE(INODE + 0 +
IT_0)
  102 CONTINUE

!--------------------------------------
! Read Model data (if any)
!--------------------------------------

      IF ( TIMEZERO ) THEN
         FILENAME = 'Main.dta'
         CALL EMTDC_OPENFILE
         SECTION = 'DATADSO:'
         CALL EMTDC_GOTOSECTION
      ENDIF

!--------------------------------------
! Generated code from module definition
!--------------------------------------


! 20:[multimeter] Multimeter
      I(1) = ( CBR((IBRCH(1)+1), SS(1)))
      I(2) = ( CBR((IBRCH(1)+2), SS(1)))
      I(3) = ( CBR((IBRCH(1)+3), SS(1)))
!
      V(1) = EMTDC_VVDC(SS(1), NT_1(1), 0)
      V(2) = EMTDC_VVDC(SS(1), NT_1(2), 0)
      V(3) = EMTDC_VVDC(SS(1), NT_1(3), 0)
!

! 30:[pgb] Output Channel 'Current'

      DO IVD1_1 = 1, 3
         PGB(IPGB+1+IVD1_1-1) = 0.36 *
I(IVD1_1)
      ENDDO

! 70:[pgb] Output Channel 'Voltage'

      DO IVD1_1 = 1, 3
         PGB(IPGB+4+IVD1_1-1) = 0.7 *
V(IVD1_1)
      ENDDO

!--------------------------------------
! Feedbacks and transfers to storage
!--------------------------------------


! Array(1:3) quantities...
      DO 103  IT_0 = 1,3
         STOF(ISTOF + 9 + IT_0) = I(IT_0)
         STOF(ISTOF + 12 + IT_0) = V(IT_0)
  103 CONTINUE

!--------------------------------------
! Close Model Data read
!--------------------------------------

      IF ( TIMEZERO ) CALL EMTDC_CLOSEFILE
      RETURN
      END
```

B. 2 Code of Proposed Wind Based DG with AC/DC/AC Converter and STATCOM/BESS

```
SUBROUTINE DSDyn()

!---------------------------------------
! Standard includes
!---------------------------------------

      INCLUDE 'nd.h'
      INCLUDE 'emtconst.h'
      INCLUDE 'emtstor.h'
      INCLUDE 's0.h'
      INCLUDE 's1.h'
      INCLUDE 's2.h'
      INCLUDE 's4.h'
      INCLUDE 'branches.h'
      INCLUDE 'pscadv3.h'
      INCLUDE 'fnames.h'
      INCLUDE 'radiolinks.h'
      INCLUDE 'matlab.h'

!---------------------------------------
! Function/Subroutine Declarations
!---------------------------------------

!     SUBR    gDyn          !
!     SUBR    TSAT21        ! Transformer
Saturation Subroutine
!     SUBR    aDyn          !
!     SUBR    ESYS65_B      ! 3-Phase RRL
Source model  (Branch Version)
!     SUBR    VControlDyn   !
!     SUBR    G6P200        ! Valve Group
Model
!     SUBR    PWMControlDyn  !

!---------------------------------------
! Variable Declarations
!---------------------------------------


! Subroutine Parameters

! Electrical Node Indexes
      INTEGER NT_9(3), NT_13, NT_14(3),
NT_17

! Control Signals
      INTEGER IT_1, IT_2, IT_3, IT_4, BRK2,
IT_5
      INTEGER IT_6
      REAL    g1(2), g2(2), g3(2), g4(2),
g5(2)
      REAL    g6(2), Vpu, Vn(3), qm, RT_1,
RT_2
      REAL    Vdcbus2, alpha2, Idc2, pl,
ql, RT_3
      REAL    RT_4, RT_5, RT_6, RT_7, RT_8,
RT_9
      REAL    RT_10, RT_11, Igto1, Vgto1,
Idi1
      REAL    Igto3, Idi3, Igto5, Idi5,
Igto4
      REAL    Vgto4, Idi4, Igto6, Idi6,
Igto2
      REAL    Idi2, In(3), Pm, dcCur,
dcVltg
      REAL    Idc1, IFdc, Itfpa, Itfpb,
Itfpc
      REAL    Itfsa, Itfsb, Itfsc, Ii(3),
Vi(3)
      REAL    Vs

! Internal Variables
      INTEGER IX, B_Stt, ISTORI
      REAL    X_KNEE, TURNS_V, P_MES, Q_MES
      REAL    E_RMS, THETA_D, SRC_V,
AO_TEMP

! Indexing variables
      INTEGER ISTOI, ISTOF, IT_0
! Storage Indexes
      INTEGER ITXRX
! Control/Monitoring
      INTEGER ISUBS, SS(1), IBRCH(1), INODE
! SS/Node/Branch/Xfmr
      INTEGER IXFMR


!---------------------------------------
! Record local indexes
!---------------------------------------

! Dsdyn <-> Dsout transfer index storage
      NTXFR = NTXFR + 1
      TXFR(NTXFR,1) = NSTOL
      TXFR(NTXFR,2) = NSTOI
      TXFR(NTXFR,3) = NSTOF

! Record Offset and Increment Storage
Counters
      ISTOI     = NSTOI
      NSTOI     = NSTOI + 7
      ISTOF     = NSTOF
      NSTOF     = NSTOF + 68
      NPGB      = NPGB + 2
      ITXRX     = NTXRX
      NTXRX     = NTXRX + 7
      INODE     = NNODE + 2
      NNODE     = NNODE + 24
      IXFMR     = NXFMR
      NXFMR     = NXFMR + 3

! Initialize Subsystem Mapping

      ISUBS = NSUBS + 0
      NSUBS = NSUBS + 1

      DO 100  IT_0 = 1,1
         SS(IT_0) = SUBS(ISUBS + IT_0)
  100 CONTINUE

! Initialize Branch Mapping.

      IBRCH(1)      = NBRCH(SS(1))
      NBRCH(SS(1)) = NBRCH(SS(1)) + 49

!---------------------------------------
```

```
! Transfers from storage arrays
!---------------------------------------

      Vpu      = STOF(ISTOF + 13)
      qm       = STOF(ISTOF + 17)
      RT_1     = STOF(ISTOF + 18)
      IT_1     = STOI(ISTOI + 1)
      RT_2     = STOF(ISTOF + 19)
      IT_2     = STOI(ISTOI + 2)
      IT_3     = STOI(ISTOI + 3)
      IT_4     = STOI(ISTOI + 4)
      Vdcbus2  = STOF(ISTOF + 20)
      alpha2   = STOF(ISTOF + 21)
      Idc2     = STOF(ISTOF + 22)
      pl       = STOF(ISTOF + 23)
      ql       = STOF(ISTOF + 24)
      RT_3     = STOF(ISTOF + 25)
      RT_4     = STOF(ISTOF + 26)
      RT_5     = STOF(ISTOF + 27)
      RT_6     = STOF(ISTOF + 28)
      BRK2     = STOI(ISTOI + 5)
      RT_7     = STOF(ISTOF + 29)
      RT_8     = STOF(ISTOF + 30)
      RT_9     = STOF(ISTOF + 31)
      RT_10    = STOF(ISTOF + 32)
      RT_11    = STOF(ISTOF + 33)
      IT_5     = STOI(ISTOI + 6)
      IT_6     = STOI(ISTOI + 7)
      Igto1    = STOF(ISTOF + 34)
      Vgto1    = STOF(ISTOF + 35)
      Idi1     = STOF(ISTOF + 36)
      Igto3    = STOF(ISTOF + 37)
      Idi3     = STOF(ISTOF + 38)
      Igto5    = STOF(ISTOF + 39)
      Idi5     = STOF(ISTOF + 40)
      Igto4    = STOF(ISTOF + 41)
      Vgto4    = STOF(ISTOF + 42)
      Idi4     = STOF(ISTOF + 43)
      Igto6    = STOF(ISTOF + 44)
      Idi6     = STOF(ISTOF + 45)
      Igto2    = STOF(ISTOF + 46)
      Idi2     = STOF(ISTOF + 47)
      Pm       = STOF(ISTOF + 51)
      dcCur    = STOF(ISTOF + 52)
      dcVltg   = STOF(ISTOF + 53)
      Idc1     = STOF(ISTOF + 54)
      IFdc     = STOF(ISTOF + 55)
      Itfpa    = STOF(ISTOF + 56)
      Itfpb    = STOF(ISTOF + 57)
      Itfpc    = STOF(ISTOF + 58)
      Itfsa    = STOF(ISTOF + 59)
      Itfsb    = STOF(ISTOF + 60)
      Itfsc    = STOF(ISTOF + 61)
      Vs       = STOF(ISTOF + 68)

! Array(1:2) quantities...
      DO 101  IT_0 = 1,2
         g1(IT_0) = STOF(ISTOF + 0 + IT_0)
         g2(IT_0) = STOF(ISTOF + 2 + IT_0)
         g3(IT_0) = STOF(ISTOF + 4 + IT_0)
         g4(IT_0) = STOF(ISTOF + 6 + IT_0)
         g5(IT_0) = STOF(ISTOF + 8 + IT_0)
         g6(IT_0) = STOF(ISTOF + 10 + IT_0)
  101 CONTINUE

! Array(1:3) quantities...
      DO 102  IT_0 = 1,3
         Vn(IT_0) = STOF(ISTOF + 13 + IT_0)
         In(IT_0) = STOF(ISTOF + 47 + IT_0)
         Ii(IT_0) = STOF(ISTOF + 61 + IT_0)
         Vi(IT_0) = STOF(ISTOF + 64 + IT_0)
  102 CONTINUE

!---------------------------------------
! Transfer from Imports
!---------------------------------------


!---------------------------------------
! Electrical Node Lookup
!---------------------------------------

      NT_13 = NODE(INODE + 16)
      NT_17 = NODE(INODE + 22)

! Array(1:3) quantities...
      DO 103  IT_0 = 1,3
         NT_9(IT_0) = NODE(INODE + 8 +
IT_0)
         NT_14(IT_0) = NODE(INODE + 16 +
IT_0)
  103 CONTINUE

!---------------------------------------
! Read Model data (if any)
!---------------------------------------

      IF ( TIMEZERO ) THEN
         FILENAME = 'Main.dta'
         CALL EMTDC_OPENFILE
         SECTION = 'DATADSD:'
         CALL EMTDC_GOTOSECTION
      ENDIF

!---------------------------------------
! Generated code from module definition
!---------------------------------------


! 10:[radiolink] Wireless connection 'g1'

      DO IX = 1,2
        g1(IX) = TX(TXRX(ITXRX+1)+IX-1)
      ENDDO

! 20:[radiolink] Wireless connection 'g2'

      DO IX = 1,2
        g2(IX) = TX(TXRX(ITXRX+2)+IX-1)
      ENDDO

! 30:[radiolink] Wireless connection 'g3'

      DO IX = 1,2
        g3(IX) = TX(TXRX(ITXRX+3)+IX-1)
      ENDDO

! 40:[radiolink] Wireless connection 'g4'

      DO IX = 1,2
        g4(IX) = TX(TXRX(ITXRX+4)+IX-1)
      ENDDO

! 50:[radiolink] Wireless connection 'g5'

      DO IX = 1,2
        g5(IX) = TX(TXRX(ITXRX+5)+IX-1)
      ENDDO

! 60:[radiolink] Wireless connection 'g6'
```

```
      DO IX = 1,2
        g6(IX) = TX(TXRX(ITXRX+6)+IX-1)
      ENDDO

! 90:[g]
      CALL gDyn()


! 120:[xfmr-3p2w] 3 Phase 2 Winding
Transformer 'tr'
!  TRANSFORMER SATURATION SUBROUTINE
      X_KNEE = 1.25
      TURNS_V = 66.3952809568
      CALL TSAT21(NT_9(1),NT_17,
NT_9(2),NT_17, NT_9(3),NT_17,SS(1),1.0,&
     &TURNS_V,0.2,X_KNEE,50.0,1.0,0.01,
0.0, 0)
!

! 160:[a]
      CALL aDyn()


! 170:[const] Real Constant
      RT_6 = 0.0

! 200:[Sequencer_Start] Sequencer (Start of
sequence of events)
! Sequencer - Start
      IT_2 = 1
! Update PSCAD Graphics
      IF ( FIRSTSTEP ) THEN
         CALL
PSCAD_AGI(71062848,STORI(NSTORI),"State")
      ENDIF
      IF ( STORI(NSTORI) .NE. IT_2 ) THEN
         CALL
PSCAD_AGI(71062848,IT_2,"State")
      ENDIF
      STORI(NSTORI) = IT_2
      NSTORI = NSTORI + 1


! 210:[Sequencer_Breaker] Sequencer
(Close/Open Breaker)
! Sequencer - Open Breaker
      IT_3 = 0
      IF ( IT_2 .EQ. 1 ) THEN
         BRK2 = 1
         IT_3 = 1
      ENDIF
! Update PSCAD Graphics
      IF ( FIRSTSTEP ) THEN
         CALL
PSCAD_AGI(71055096,STORI(NSTORI),"State")
      ENDIF
      IF ( STORI(NSTORI) .NE. IT_3 ) THEN
         CALL
PSCAD_AGI(71055096,IT_3,"State")
      ENDIF
      STORI(NSTORI) = IT_3
      NSTORI = NSTORI + 1
      BRK2 = BRK2

! 220:[Sequencer_Wait] Sequencer (Wait for
an event)
! Sequencer - Wait Until Specified Time
      IT_4 = 0
      IF ( IT_3 .EQ. 1 ) THEN
         IF ( TIME.GT.7.5 ) THEN
            IT_4 = 1
         ENDIF
      ENDIF
! Update PSCAD Graphics
      IF ( FIRSTSTEP ) THEN
         CALL
PSCAD_AGI(71063664,STORI(NSTORI),"State")
      ENDIF
      IF ( STORI(NSTORI) .NE. IT_4 ) THEN
         CALL
PSCAD_AGI(71063664,IT_4,"State")
      ENDIF
      STORI(NSTORI) = IT_4
      NSTORI = NSTORI + 1

! 230:[Sequencer_Breaker] Sequencer
(Close/Open Breaker)
! Sequencer - Close Breaker
      IT_6 = 0
      IF ( IT_4 .EQ. 1 ) THEN
         BRK2 = 0
         IT_6 = 1
      ENDIF
! Update PSCAD Graphics
      IF ( FIRSTSTEP ) THEN
         CALL
PSCAD_AGI(71060400,STORI(NSTORI),"State")
      ENDIF
      IF ( STORI(NSTORI) .NE. IT_6 ) THEN
         CALL
PSCAD_AGI(71060400,IT_6,"State")
      ENDIF
      STORI(NSTORI) = IT_6
      NSTORI = NSTORI + 1
      BRK2 = BRK2

! 240:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: GTO
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+10), 0.005, 100000000.0, NI&
     &NT(g4(1)), g4(2), 2, 0, 100000.0,
100000.0, 0.0, 0.0)

! 250:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: GTO
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+1), 0.005, 100000000.0, NIN&
     &T(g1(1)), g1(2), 2, 0, 100000.0,
100000.0, 0.0, 0.0)

! 260:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: Diode
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+12), 0.005, 100000000.0, 1,&
     & 0.0, 0, 0, 100000.0, 100000.0, 0.0,
0.0)

! 270:[const] Real Constant
      RT_9 = 1.88

! 280:[vdcl] Voltage Dependent Current
Limits
!  VDCL3 - Generic Voltage Dependant
Current Limiter
!
```

```
      CALL VDCL3(  RT_9 , Vdcbus2 , -2,
1.0, 0.06, 0.5, 0.7, 0.02, 10.0,&
     & RT_10)
!

! 290:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: Diode
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+3), 0.005, 100000000.0, 1, &
     &0.0, 0, 0, 100000.0, 100000.0, 0.0,
0.0)

! 300:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: GTO
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+13), 0.005, 100000000.0, NI&
     &NT(g6(1)), g6(2), 2, 0, 100000.0,
100000.0, 0.0, 0.0)

! 310:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: GTO
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+4), 0.005, 100000000.0, NIN&
     &T(g3(1)), g3(2), 2, 0, 100000.0,
100000.0, 0.0, 0.0)

! 320:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: Diode
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+15), 0.005, 100000000.0, 1,&
     & 0.0, 0, 0, 100000.0, 100000.0, 0.0,
0.0)

! 330:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: Diode
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+6), 0.005, 100000000.0, 1, &
     &0.0, 0, 0, 100000.0, 100000.0, 0.0,
0.0)

! 340:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: GTO
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+16), 0.005, 100000000.0, NI&
     &NT(g2(1)), g2(2), 2, 0, 100000.0,
100000.0, 0.0, 0.0)

! 350:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: GTO
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+7), 0.005, 100000000.0, NIN&
     &T(g5(1)), g5(2), 2, 0, 100000.0,
100000.0, 0.0, 0.0)

! 360:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: Diode
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+18), 0.005, 100000000.0, 1,&
     & 0.0, 0, 0, 100000.0, 100000.0, 0.0,
0.0)

! 370:[peswitch] Power electronic switch
! EMTDC_PESWITCH Power Electronic Switch
Model: Diode
      CALL EMTDC_PESWITCH2(SS(1),
(IBRCH(1)+9), 0.005, 100000000.0, 1, &
     &0.0, 0, 0, 100000.0, 100000.0, 0.0,
0.0)

! 390:[source1] Single Phase Voltage Source
Model 1 'dc'
!  Single Phase Source: dc
      SRC_V = 0.5*SQRT_3*SQRT_1BY2
!
      CALL ESYS65_B(SS(1),
(IBRCH(1)+39),0,0,0,0,0,
SS(1),N&
     &T_13,0,0,            -0.0, 0.001,
0.0, 0.0, 0.0,            50.0, &
     &0.0, 0, SRC_V, 0.0,            1.0,
1.0, 1.0,            PI_BY2, 3&
     &50.0, 100.0,            1.0, 1.0,
1.0, 1.0,            1.0, 1.0, 1&
     &.0, 0,            P_MES, Q_MES,
E_RMS, THETA_D)

! 400:[VControl]
      CALL VControlDyn(qm, Vpu, RT_3)


! 410:[polpi5] Generic Current Controller
!  POLPI5 - Generic Current Controller
!
      CALL POLPI5( RT_10 , Idc2 ,
0.0 , 0.1 , 0.0 , 3.142 , &
     &5.0 , 0.02 ,            RT_11 ,
alpha2 )
!

! 420:[g6p200] 6 Pulse Bridge
!  G6P200 Valve Group Model
      AO_TEMP = RT_6*PI_BY180
      CALL G6P200( SS(1) , NT_14(1) ,
NT_14(2) , NT_14(3) ,   (IBRCH(1)+&
     &23) ,  (IBRCH(1)+28) ,  (IBRCH(1)+24)
,   (IBRCH(1)+26) ,  (IBRCH(&
     &1)+25) ,  (IBRCH(1)+27) ,  AO_TEMP ,
10.0 , 100.0 ,   50.0, NINT(R&
     &T_1), 0,  0, RT_4, RT_5, 0.01,
1000000.0, 0.0, 100000.0, 0.0)
!
!

! 430:[breaker1] Single Phase Breaker
'BRK2'
      ISTORI = NSTORI
      NSTORI = NSTORI + 1
! Single phase breaker
      CALL EMTDC_BREAKER1(SS(1),
(IBRCH(1)+38),0.005,1000000.0,0.0,0,NIN&
     &T(1.0-REAL(BRK2)))
      B_Stt = 2*E_BtoI(OPENBR(
(IBRCH(1)+38),SS(1)))
      IF (FIRSTSTEP .OR. (STORI(ISTORI+0)
.NE. B_Stt)) THEN
         CALL
PSCAD_AGI(71051832,B_Stt,"BOpen")
      ENDIF
      STORI(ISTORI+0) = 2*E_BtoI(OPENBR(
(IBRCH(1)+38),SS(1)))

! 440:[g6p200] 6 Pulse Bridge
```

```
!  G6P200 Valve Group Model
      CALL G6P200( SS(1) , NT_9(1) ,
NT_9(2) , NT_9(3) ,   (IBRCH(1)+41)&
     & ,  (IBRCH(1)+46) ,  (IBRCH(1)+42) ,
(IBRCH(1)+44) ,  (IBRCH(1)+&
     &43) ,  (IBRCH(1)+45) ,  alpha2 , 10.0
, 100.0 ,   50.0, NINT(RT_2)&
     &, 0,  0, RT_7, RT_8, 0.01, 1000000.0,
0.0, 100000.0, 0.0)
!
!

! 480:[PWMControl]
      CALL PWMControlDyn(RT_3)


!---------------------------------------
! Feedbacks and transfers to storage
!---------------------------------------

      STOF(ISTOF + 13) = Vpu
      STOF(ISTOF + 17) = qm
      STOF(ISTOF + 18) = RT_1
      STOI(ISTOI + 1) = IT_1
      STOF(ISTOF + 19) = RT_2
      STOI(ISTOI + 2) = IT_2
      STOI(ISTOI + 3) = IT_3
      STOI(ISTOI + 4) = IT_4
      STOF(ISTOF + 20) = Vdcbus2
      STOF(ISTOF + 21) = alpha2
      STOF(ISTOF + 22) = Idc2
      STOF(ISTOF + 23) = pl
      STOF(ISTOF + 24) = ql
      STOF(ISTOF + 25) = RT_3
      STOF(ISTOF + 26) = RT_4
      STOF(ISTOF + 27) = RT_5
      STOF(ISTOF + 28) = RT_6
      STOI(ISTOI + 5) = BRK2
      STOF(ISTOF + 29) = RT_7
      STOF(ISTOF + 30) = RT_8
      STOF(ISTOF + 31) = RT_9
      STOF(ISTOF + 32) = RT_10
      STOF(ISTOF + 33) = RT_11
      STOI(ISTOI + 6) = IT_5
      STOI(ISTOI + 7) = IT_6
      STOF(ISTOF + 34) = Igto1
      STOF(ISTOF + 35) = Vgto1
      STOF(ISTOF + 36) = Idi1
      STOF(ISTOF + 37) = Igto3
      STOF(ISTOF + 38) = Idi3
      STOF(ISTOF + 39) = Igto5
      STOF(ISTOF + 40) = Idi5
      STOF(ISTOF + 41) = Igto4
      STOF(ISTOF + 42) = Vgto4
      STOF(ISTOF + 43) = Idi4
      STOF(ISTOF + 44) = Igto6
      STOF(ISTOF + 45) = Idi6
      STOF(ISTOF + 46) = Igto2
      STOF(ISTOF + 47) = Idi2
      STOF(ISTOF + 51) = Pm
      STOF(ISTOF + 52) = dcCur
      STOF(ISTOF + 53) = dcVltg
      STOF(ISTOF + 54) = Idc1
      STOF(ISTOF + 55) = IFdc
      STOF(ISTOF + 56) = Itfpa
      STOF(ISTOF + 57) = Itfpb
      STOF(ISTOF + 58) = Itfpc
      STOF(ISTOF + 59) = Itfsa
      STOF(ISTOF + 60) = Itfsb
      STOF(ISTOF + 61) = Itfsc
      STOF(ISTOF + 68) = Vs

! Array(1:2) quantities...
      DO 104  IT_0 = 1,2
         STOF(ISTOF + 0 + IT_0) = g1(IT_0)
         STOF(ISTOF + 2 + IT_0) = g2(IT_0)
         STOF(ISTOF + 4 + IT_0) = g3(IT_0)
         STOF(ISTOF + 6 + IT_0) = g4(IT_0)
         STOF(ISTOF + 8 + IT_0) = g5(IT_0)
         STOF(ISTOF + 10 + IT_0) = g6(IT_0)
  104 CONTINUE

! Array(1:3) quantities...
      DO 105  IT_0 = 1,3
         STOF(ISTOF + 13 + IT_0) = Vn(IT_0)
         STOF(ISTOF + 47 + IT_0) = In(IT_0)
         STOF(ISTOF + 61 + IT_0) = Ii(IT_0)
         STOF(ISTOF + 64 + IT_0) = Vi(IT_0)
  105 CONTINUE

!---------------------------------------
! Transfer to Exports
!---------------------------------------

!---------------------------------------
! Close Model Data read
!---------------------------------------

      IF ( TIMEZERO ) CALL EMTDC_CLOSEFILE
      RETURN
      END

!==========================================
=============================

      SUBROUTINE DSOut()

!---------------------------------------
! Standard includes
!---------------------------------------

      INCLUDE 'nd.h'
      INCLUDE 'emtconst.h'
      INCLUDE 'emtstor.h'
      INCLUDE 's0.h'
      INCLUDE 's1.h'
      INCLUDE 's2.h'
      INCLUDE 's4.h'
      INCLUDE 'branches.h'
      INCLUDE 'pscadv3.h'
      INCLUDE 'fnames.h'
      INCLUDE 'radiolinks.h'
      INCLUDE 'matlab.h'

!---------------------------------------
! Function/Subroutine Declarations
!---------------------------------------

      REAL    EMTDC_VVDC    !
!     SUBR    gOut          !
      REAL    P3PH3         !
      REAL    Q3PH3         !
      REAL    VM3PH2        ! '3 Phase RMS
Voltage Measurement'
!     SUBR    EMTDC_X2COMP  ! 'Comparator
with Interpolation'
!     SUBR    aOut          !
      REAL    VBRANCH       ! Voltage
across the branch
!     SUBR    VControlOut   !
```

```
!     SUBR    PWMControlOut  !

!---------------------------------------
! Variable Declarations
!---------------------------------------


! Electrical Node Indexes
      INTEGER NT_4(3), NT_7, NT_11(3),
NT_13
      INTEGER NT_16

! Control Signals
      REAL    Vpu, Vn(3), qm, RT_1, RT_2,
Vdcbus2
      REAL    Idc2, pl, ql, Igto1, Vgto1,
Idi1
      REAL    Igto3, Idi3, Igto5, Idi5,
Igto4
      REAL    Vgto4, Idi4, Igto6, Idi6,
Igto2
      REAL    Idi2, In(3), Pm, dcCur,
dcVltg
      REAL    Idc1, IFdc, Itfpa, Itfpb,
Itfpc
      REAL    Itfsa, Itfsb, Itfsc, Ii(3),
Vi(3)
      REAL    Vs

! Internal Variables
      INTEGER IX
      REAL    RVD1_1, RVD2_1(2)

! Indexing variables
      INTEGER ISTOL, ISTOI, ISTOF, IT_0
! Storage Indexes
      INTEGER IPGB, ITXRX
! Control/Monitoring
      INTEGER ISUBS, SS(1), IBRCH(1), INODE
! SS/Node/Branch/Xfmr
      INTEGER IXFMR


!---------------------------------------
! Record local indexes
!---------------------------------------

! Dsdyn <-> Dsout transfer index storage
      NTXFR = NTXFR + 1
      ISTOL = TXFR(NTXFR,1)
      ISTOI = TXFR(NTXFR,2)
      ISTOF = TXFR(NTXFR,3)

! Record Offset and Increment Storage
Counters
      IPGB      = NPGB
      NPGB      = NPGB + 2
      ITXRX     = NTXRX
      NTXRX     = NTXRX + 7
      INODE     = NNODE + 2
      NNODE     = NNODE + 24
      IXFMR     = NXFMR
      NXFMR     = NXFMR + 3

! Initialize Subsystem Mapping

      ISUBS = NSUBS + 0
      NSUBS = NSUBS + 1

      DO 100  IT_0 = 1,1
         SS(IT_0) = SUBS(ISUBS + IT_0)
  100 CONTINUE

! Initialize Branch Mapping.

      IBRCH(1)     = NBRCH(SS(1))
      NBRCH(SS(1)) = NBRCH(SS(1)) + 49

!---------------------------------------
! Transfers from storage arrays
!---------------------------------------

      Vpu      = STOF(ISTOF + 13)
      qm       = STOF(ISTOF + 17)
      RT_1     = STOF(ISTOF + 18)
      RT_2     = STOF(ISTOF + 19)
      Vdcbus2  = STOF(ISTOF + 20)
      Idc2     = STOF(ISTOF + 22)
      pl       = STOF(ISTOF + 23)
      ql       = STOF(ISTOF + 24)
      Igto1    = STOF(ISTOF + 34)
      Vgto1    = STOF(ISTOF + 35)
      Idi1     = STOF(ISTOF + 36)
      Igto3    = STOF(ISTOF + 37)
      Idi3     = STOF(ISTOF + 38)
      Igto5    = STOF(ISTOF + 39)
      Idi5     = STOF(ISTOF + 40)
      Igto4    = STOF(ISTOF + 41)
      Vgto4    = STOF(ISTOF + 42)
      Idi4     = STOF(ISTOF + 43)
      Igto6    = STOF(ISTOF + 44)
      Idi6     = STOF(ISTOF + 45)
      Igto2    = STOF(ISTOF + 46)
      Idi2     = STOF(ISTOF + 47)
      Pm       = STOF(ISTOF + 51)
      dcCur    = STOF(ISTOF + 52)
      dcVltg   = STOF(ISTOF + 53)
      Idc1     = STOF(ISTOF + 54)
      IFdc     = STOF(ISTOF + 55)
      Itfpa    = STOF(ISTOF + 56)
      Itfpb    = STOF(ISTOF + 57)
      Itfpc    = STOF(ISTOF + 58)
      Itfsa    = STOF(ISTOF + 59)
      Itfsb    = STOF(ISTOF + 60)
      Itfsc    = STOF(ISTOF + 61)
      Vs       = STOF(ISTOF + 68)

! Array(1:3) quantities...
      DO 101  IT_0 = 1,3
         Vn(IT_0) = STOF(ISTOF + 13 + IT_0)
         In(IT_0) = STOF(ISTOF + 47 + IT_0)
         Ii(IT_0) = STOF(ISTOF + 61 + IT_0)
         Vi(IT_0) = STOF(ISTOF + 64 + IT_0)
  101 CONTINUE

!---------------------------------------
! Electrical Node Lookup
!---------------------------------------

      NT_7  = NODE(INODE + 8)
      NT_13 = NODE(INODE + 16)
      NT_16 = NODE(INODE + 21)

! Array(1:3) quantities...
      DO 102  IT_0 = 1,3
         NT_4(IT_0) = NODE(INODE + 0 +
IT_0)
         NT_11(IT_0) = NODE(INODE + 12 +
IT_0)
  102 CONTINUE
```

```
!----------------------------------------
! Read Model data (if any)
!----------------------------------------

      IF ( TIMEZERO ) THEN
         FILENAME = 'Main.dta'
         CALL EMTDC_OPENFILE
         SECTION = 'DATADSO:'
         CALL EMTDC_GOTOSECTION
      ENDIF

!----------------------------------------
! Generated code from module definition
!----------------------------------------


! 70:[ammeter] Current Meter 'Idc2'
      Idc2 = ( CBR((IBRCH(1)+40), SS(1)))

! 80:[voltmeter] Voltmeter (Line - Line)
'Vdcbus2'
      Vdcbus2 = EMTDC_VVDC(SS(1), NT_7,
NT_16)

! 90:[g]
      CALL gOut()


! 100:[ammeter] Current Meter 'Idc1'
      Idc1 = ( CBR((IBRCH(1)+47), SS(1)))

! 110:[multimeter] Multimeter
      Ii(1) = ( CBR((IBRCH(1)+35), SS(1)))
      Ii(2) = ( CBR((IBRCH(1)+36), SS(1)))
      Ii(3) = ( CBR((IBRCH(1)+37), SS(1)))
!
      Vi(1) = EMTDC_VVDC(SS(1), NT_4(1), 0)
      Vi(2) = EMTDC_VVDC(SS(1), NT_4(2), 0)
      Vi(3) = EMTDC_VVDC(SS(1), NT_4(3), 0)
!
!
      RVD1_1 = P3PH3(SS(1), (IBRCH(1)+35),
(IBRCH(1)+36), (IBRCH(1)+37),&
     &0.02,0)
      pl = RVD1_1
!
      RVD1_1 = Q3PH3(SS(1), (IBRCH(1)+35),
(IBRCH(1)+36), (IBRCH(1)+37),&
     &0.02,0)
      ql = RVD1_1
!
      RVD1_1 = VM3PH2(SS(1), NT_4(1),
NT_4(2), NT_4(3), 0.02)
      Vs = RVD1_1
!
!

! 120:[xfmr-3p2w] 3 Phase 2 Winding
Transformer 'tr'
      Itfpa = CDCTR(1,(IXFMR + 1))
      Itfpb = CDCTR(1,(IXFMR + 2))
      Itfpc = CDCTR(1,(IXFMR + 3))
      Itfsa = CDCTR(2,(IXFMR + 1))
      Itfsb = CDCTR(2,(IXFMR + 2))
      Itfsc = CDCTR(2,(IXFMR + 3))

! 150:[compare] Single Input Level
Comparator
!
      CALL
EMTDC_X2COMP(0,0,0.0,Vdcbus2,0.0,0.0,1.0,RV
D2_1)
      RT_2 = RVD2_1(1)

! 160:[a]
      CALL aOut()


! 180:[compare] Single Input Level
Comparator
!
      CALL
EMTDC_X2COMP(0,0,0.0,Vdcbus2,0.0,0.0,1.0,RV
D2_1)
      RT_1 = RVD2_1(1)

! 190:[multimeter] Multimeter
      In(1) = ( CBR((IBRCH(1)+19), SS(1)))
      In(2) = ( CBR((IBRCH(1)+20), SS(1)))
      In(3) = ( CBR((IBRCH(1)+21), SS(1)))
!
      Vn(1) = EMTDC_VVDC(SS(1), NT_11(1),
0)
      Vn(2) = EMTDC_VVDC(SS(1), NT_11(2),
0)
      Vn(3) = EMTDC_VVDC(SS(1), NT_11(3),
0)
!
!
      RVD1_1 = P3PH3(SS(1), (IBRCH(1)+19),
(IBRCH(1)+20), (IBRCH(1)+21),&
     &0.01,0)
      Pm = RVD1_1
!
      RVD1_1 = Q3PH3(SS(1), (IBRCH(1)+19),
(IBRCH(1)+20), (IBRCH(1)+21),&
     &0.01,0)
      Qm = RVD1_1
!
      RVD1_1 = 0.00869565217391 *
VM3PH2(SS(1), NT_11(1), NT_11(2), NT_1&
     &1(3), 0.01)
      Vpu = RVD1_1
!
!

! 240:[peswitch] Power electronic switch
      Igto4 = ( CBR((IBRCH(1)+10), SS(1)))
      Vgto4 = VBRANCH(SS(1), (IBRCH(1)+10))

! 250:[peswitch] Power electronic switch
      Igto1 = ( CBR((IBRCH(1)+1), SS(1)))
      Vgto1 = VBRANCH(SS(1), (IBRCH(1)+1))

! 260:[peswitch] Power electronic switch
      Idi4 = ( CBR((IBRCH(1)+12), SS(1)))

! 290:[peswitch] Power electronic switch
      Idi1 = ( CBR((IBRCH(1)+3), SS(1)))

! 300:[peswitch] Power electronic switch
      Igto6 = ( CBR((IBRCH(1)+13), SS(1)))

! 310:[peswitch] Power electronic switch
      Igto3 = ( CBR((IBRCH(1)+4), SS(1)))

! 320:[peswitch] Power electronic switch
      Idi6 = ( CBR((IBRCH(1)+15), SS(1)))
```

```
! 330:[peswitch] Power electronic switch
      Idi3 = ( CBR((IBRCH(1)+6), SS(1)))

! 340:[peswitch] Power electronic switch
      Igto2 = ( CBR((IBRCH(1)+16), SS(1)))

! 350:[peswitch] Power electronic switch
      Igto5 = ( CBR((IBRCH(1)+7), SS(1)))

! 360:[peswitch] Power electronic switch
      Idi2 = ( CBR((IBRCH(1)+18), SS(1)))

! 370:[peswitch] Power electronic switch
      Idi5 = ( CBR((IBRCH(1)+9), SS(1)))

! 380:[multimeter] Multimeter
      dcCur = ( CBR((IBRCH(1)+22), SS(1)))
!
      dcVltg = EMTDC_VVDC(SS(1), NT_13, 0)

! 390:[source1] Single Phase Voltage Source
Model 1 'dc'
      IFdc = ( CBR((IBRCH(1)+39), SS(1)))

! 400:[VControl]
      CALL VControlOut()


! 430:[breaker1] Single Phase Breaker
'BRK2'
! Single phase breaker current



! 450:[pgb] Output Channel '<Untitled>'

      PGB(IPGB+1) = ql

! 460:[pgb] Output Channel '<Untitled>'

      PGB(IPGB+2) = pl

! 470:[radiolink] Wireless connection 'Vn'

      DO IX = 1,3
        TX(TXRX(ITXRX+7)+IX-1) = Vn(IX)
      ENDDO

! 480:[PWMControl]
      CALL PWMControlOut()


!---------------------------------------
```

```
! Feedbacks and transfers to storage
!---------------------------------------

      STOF(ISTOF + 13) = Vpu
      STOF(ISTOF + 17) = qm
      STOF(ISTOF + 18) = RT_1
      STOF(ISTOF + 19) = RT_2
      STOF(ISTOF + 20) = Vdcbus2
      STOF(ISTOF + 22) = Idc2
      STOF(ISTOF + 23) = pl
      STOF(ISTOF + 24) = ql
      STOF(ISTOF + 34) = Igto1
      STOF(ISTOF + 35) = Vgto1
      STOF(ISTOF + 36) = Idi1
      STOF(ISTOF + 37) = Igto3
      STOF(ISTOF + 38) = Idi3
      STOF(ISTOF + 39) = Igto5
      STOF(ISTOF + 40) = Idi5
      STOF(ISTOF + 41) = Igto4
      STOF(ISTOF + 42) = Vgto4
      STOF(ISTOF + 43) = Idi4
      STOF(ISTOF + 44) = Igto6
      STOF(ISTOF + 45) = Idi6
      STOF(ISTOF + 46) = Igto2
      STOF(ISTOF + 47) = Idi2
      STOF(ISTOF + 51) = Pm
      STOF(ISTOF + 52) = dcCur
      STOF(ISTOF + 53) = dcVltg
      STOF(ISTOF + 54) = Idc1
      STOF(ISTOF + 55) = IFdc
      STOF(ISTOF + 56) = Itfpa
      STOF(ISTOF + 57) = Itfpb
      STOF(ISTOF + 58) = Itfpc
      STOF(ISTOF + 59) = Itfsa
      STOF(ISTOF + 60) = Itfsb
      STOF(ISTOF + 61) = Itfsc
      STOF(ISTOF + 68) = Vs

! Array(1:3) quantities...
      DO 103  IT_0 = 1,3
         STOF(ISTOF + 13 + IT_0) = Vn(IT_0)
         STOF(ISTOF + 47 + IT_0) = In(IT_0)
         STOF(ISTOF + 61 + IT_0) = Ii(IT_0)
         STOF(ISTOF + 64 + IT_0) = Vi(IT_0)
  103 CONTINUE

!---------------------------------------
! Close Model Data read
!---------------------------------------

      IF ( TIMEZERO ) CALL EMTDC_CLOSEFILE
      RETURN
      END
```

PUBLICATIONS

Book Chapter (Springer)

1. N. K. Roy and A. Das (2017), Prospects of Renewable Energy Sources, Renewable Energy and the Environment, Springer, Print ISBN: 978-981-10-7286-4.

Conference Paper

1. A. Das and N. K. Roy, “Reduction of harmonics distortion and voltage sag of PMSG based wind energy systems connected to distribution networks,” IEEE Region 10 Humanitarian Technology Conference, December 2017, Dhaka, Bangladesh.

2. A. Das, N. K. Roy, and H. R. Pota, “Power quality analysis of distributed wind generation systems,” 3rd International Conference on Electrical Information and Communication Technology, December 2017, Khulna, Bangladesh.