DESIGN AND ANALYSIS OF SYNCHRONVERTER BASED VIRTUAL INERTIA CONTROL FOR HYBRID POWER PLANTS

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Abstract

The shifting to a low carbon community is the actual driving force replacing the conventional power systems to escalate the volume of non synchronous generators i.e. renewable energy resources for the purpose of meeting the local load demand. Since the DG resources are intermittent in nature and load profile continuously varies with time, this causes dynamic frequency stability issues since these resources do not provide sufficient inertia to cater the frequency stability problems because of the presence of power electronics based converters used for their grid integration. To overcome this issue, the idea of virtual inertia introduction in such systems is implemented. A synchronverter is a 3-φ voltage source inverter accompanying a DC energy source that imitates the behavior of a synchronous generator thus offers a mechanism for the control of these RES in grid connected mode. The synchronverter behaves like a self-synchronization unit and tries to synchronize itself with the grid, thus providing the voltage and frequency support to the grid. This thesis presents a PV-Wind hybrid system simulated in MATLAB/Simulink using synchronverter to cater the frequency and voltage stability problems. The model is operated in grid connected mode and the effect of load variation and the provision of reactive load to the system parameters are being monitored. The features of synchronous generator including the frequency droop and voltage droop are properly observed by the system presented.

Keywords: Hybrid renewable energy resources, virtual inertia, PWM based synchronverters, Droop control, Matlab/Simulink

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- Osama Bin Muzaffar, Abasin Ulasyar , Haris Sheh Zad , Abraiz Khattak , Kashif Imran , Shibli Nisar **"Design and Analysis of Synchronverter Based Virtual Inertia Control for Hybrid Power Plants"** 3rd International Conference on Sustainable Energy Technologies (ICSET 2021) Aug, 2021 at USPCASE UET Peshawar, Pakistan

List of Abbreviations

VSG	Virtual synchronous generator
RES	Renewable energy sources
DG	distributed generation
VI	Virtual inertia
Kp	Proportional gain
MPPT	Maximum power point tracking
PV	Photovoltaic
WEG	Wind energy generation
PMSG	Permanent magnet synchronous generator
rpm	revolutions per minute
ESS	Energy storage system
ROCOF	Rate of change of frequency
PLL	Phase locked loop
WT	Wind turbine

Chapter 1: Introduction

1.1 Background:-

The demand of the clean and green energy in the modern power system is escalating day by day. With a shift in policy of Pakistan to utilize the renewable energy resources in the last decade, the country is currently shifting to harness as much energy as applicable to meet the local load demand and also to reduce the burden from the existing conventional technologies. Hybrid renewable energy systems consisting of widely available energy resources like PV, Hydro and Wind energy are gaining maximum attentions because of the resiliency of these systems to operate in grid connected as well as in islanded mode. Within a limited time, the cost of solar system has been through an exponential drop that caused its uses to increase rapidly. PV and Wind systems mostly complement one another. PV systems don't have any built-in inertia because of having no moving parts. Although WEG system contains rotational parts but these resources are coupled to the utility grid by means of certain power electronics based converters which totally decouples the inertia of wind turbines. Also the intermittent nature of these resources and the behavior of load fluctuation gives arise to certain issues that need to be addressed.

1.2 Motivation:-

Energy demand is growing by more than 9% per annum in Pakistan. It is expected that energy demand will be enhanced 8-fold by 2030 and 20-fold by 2050 in Pakistan [1]. In our country, the energy needs are fulfilled using the fossil fuels. About 64% of energy mix comes through the fossil fuels [2]. This can lead not only the burden on the economy of country but also raises the concerns about the greenhouse effect, global warming, CO_2emission and irregular weather patterns. Pakistan can bring in use the freely and widely available distributed energy from the sun for improving the socio-economic lifestyle of the people residing in remote areas. Also a huge potential of wind energy is available in the coastal belt of Sindh and Baluchistan. Recent stats shows that the total RES potential in Pakistan is almost 167.7 GW which is 8 times more than the total electricity demand of 21 GW of the country. The government has issued a white paper in 2005 to meet 10% of total energy demand from renewable energy sources by 2012 [3]. But the increase in energy utilization from these RES demands certain control strategies for interfacing these systems with the electrical grid. Since the conventional energy is generated using the systems that are composed of huge synchronous machines. The inherent inertia in the rotor of these giant machines is able to support system instability and damping properties during the event of any disturbance or any instability events [4]. Increase in energy harvesting from these RES can lower down the inertia of the systems to these disturbances due to the fact that DG resources have no or very small built-in inertia because of the absence or decoupled rotating mass(in case of PV and wind).This can result in certain instability event including the power imbalance, frequency deviation that can cause tripping of frequency protection relays along-with transient instability of the system [4].

Therefore, as a solution to the problems introduced due to grid connected renewable energy sources (RES), a virtual inertia (VI) termed as an artificial inertia or synthetic inertia based control system strategy has been presented. Enormous research is carried out to implement it using conventional synchronous inverters commonly termed as the synchronverters [5]. The inverter can function like the conventional synchronous generator that can emulate inertia to the system in the event of certain disturbance.

1.3 Objective:-

There are many methods available for creating the virtual or artificial inertia. Till now, a lot of work has been done to implement it in the grid connected or islanded mode standalone systems. This thesis presents the emulation of the virtual inertia using the synchronverter based VSG topology. The hybrid system comprised of PV & Wind system and the effect of various disturbances in the form of adding active and reactive powers to the system is being analyzed. Also the effect to the voltage and current profile graphs of the system in grid connected mode are being observed. The effect of these operating conditions on the frequency regulation and the time taken by the system to restore the frequency to its supposed value is also being monitored.

1.4 Organization of thesis:-

This thesis is categorized into five chapters. Chapter 1 gives the introduction, motivation and objective of the work. Chapter 2 provides the literature review about the previously used virtual inertia provision topologies and brief overview of the proposed scheme i.e. synchronverter based hybrid RES. Chapter 3 covers the methodology used to design the controller for the synchronous inverter accompanying the designing of PV and WEG system. Simulation results for synchronverter based virtual inertia controlled hybrid renewable energy sources in different operating conditions are discussed in chapter 4 while chapter 5 concludes the thesis.

References:-

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[5] Zhong, Q. C., & Weiss, G. (2010). Synchronverters: Inverters that mimic synchronous generators. *IEEE transactions on industrial electronics*, *58*(4), 1259-1267.

Chapter 2: Literature Review

2.1 Inertia in Power Systems:-

2.1.1 Inertia in Conventional Power Systems:-

The inertia of the system is always considered to be as one of the essential parameter upon which the synchronized and proper operation of the present day power is based. The inertia in common terms is considered to be a property of a body to resist certain change in its state of operation in the event of sudden disturbance. Inertia in power systems alludes to the energy available in the huge rotating generators/alternators and in few industrial motors which maintains its rotation in the event of certain disturbance without any dip in the speed of rotation [1].

However, in the practical scenario of the power system, there occurs the power mismatch between the generation and demand frequently which can lead to the deviation in the frequency of the system as shown in the figure 2-1.

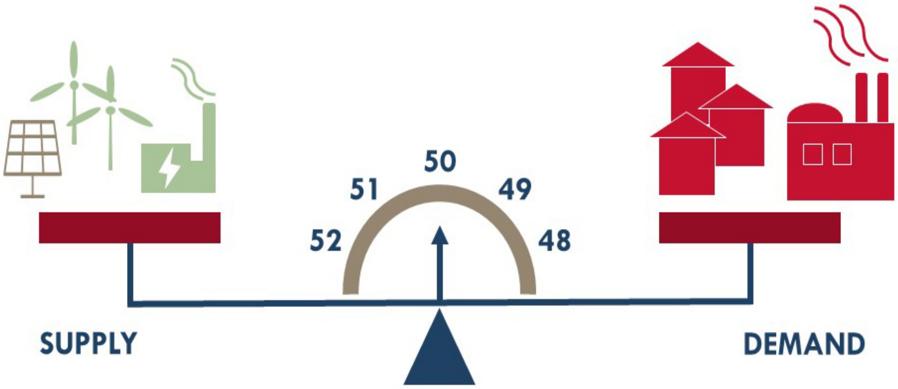

Figure 2-1: Frequency deviation in power system [2]

This is due to the principle that these systems provide inertia at the same frequency as the utility grid when they are rotating due to their synchronized operation[3]. Whenever there is variance between demand and supply of power, a frequency change will occur because the speed of the rotating masses will be changed. The frequency will fluctuate because the machines that manage the frequency are synchronous machines and are synchronized to the system frequency with their rotating parts. If the input mechanical power to the generators exceeds the electrical load, the rotating masses will store the excess energy by accelerating the rotating part. This will shoot up the system frequency. If the load is too large in proportion to the mechanical power, the rotating masses will provide the lacking energy by using its stored kinetic energy by decelerating the rotating parts. This will cause a drop in the system frequency [4].

2.1.2 Inertia in Renewable Energy Based Systems:-

With the increase in penetration of RES specially the PV(solar) and WEG systems in the existing power systems, the inertia of the system got a drastic decrease since these systems have null or very small amount of built in inertia. This is due to the fact that the PV system contains no rotating parts. Although the WEG systems consist of rotational parts but they are decoupled from the system due to the presence of power electronics based converters. To overcome this issue, a virtual or artificial inertia is designed for these systems which can be able to mimic the function of conventional synchronous generators and bring the system back to its nominal operating conditions in the event of any disturbance as shown in the figure 2-2

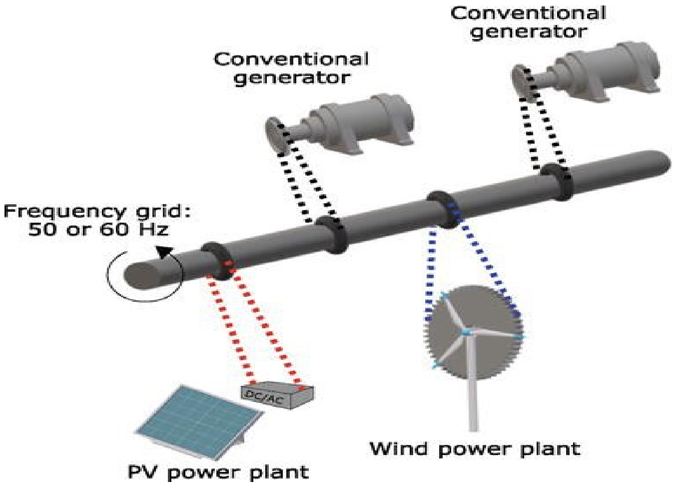

Figure 2-2: RES functioning like conventional synchronous generators [5]

2.1.3 Virtual Inertia:-

Virtual inertia is termed as the artificially manufactured inertia which can function somewhat in a similar manner to the conventional inertia preserved in the huge masses of the synchronous generators. Virtual inertia can be defined as the combination of RES, ESS (battery/supercapacitor etc), power electronics based converters/inverters and a control algorithm which can function in a similar manner as a synchronous generator to the grid [6]. A virtual inertia can inject into or absorb active power from the system in order to ensure the dynamic stability of the system. This function can be performed by operating the inverter in a similar manner as the synchronous generator. The inverter therefore can be termed as synchronverter as shown in figure 2-3.

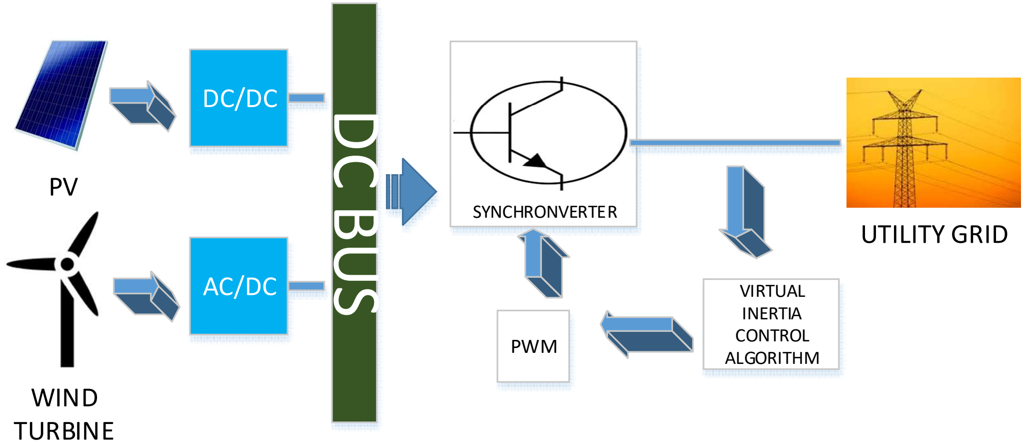

Figure 2-3: Virtual inertia emulation using synchronverters

2.2 Different Modules of Proposed System:-

2.2.1 Photovoltaic (PV) System:-

A PV system is comprised of interconnected PV panels which are connected to a DC-DC boost converter and an inverter linked to the grid. The inputs to the PV module are solar irradiance and operating temperature. The PV module converts the input solar irradiance into an electrical output. After that the DC-DC converter commonly known as boost converter steps up the DC output voltage from the PV panel to a higher voltage that is demanded by the inverter. The inverter finally converts this voltage into an AC voltage which can then be supplied into the grid. To extract maximum power from the system, the system is connected with the maximum power point tracking (MPPT) controller which optimizes the output from the solar panel under varying operating conditions. The output parameters of PV system fluctuates according to the variation in the irradiance level as shown in figure 2-4

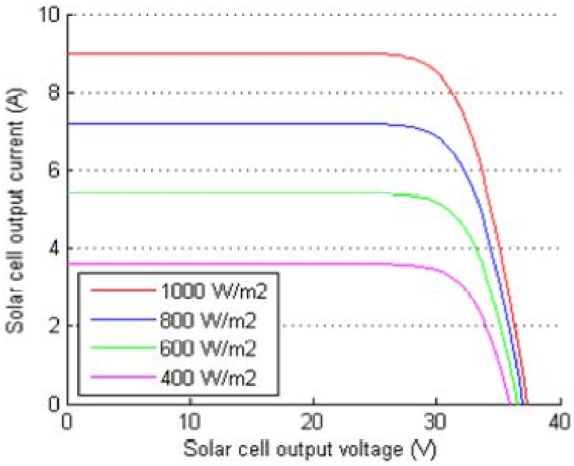

Figure 2-4: I-V curve of solar panels at different irradiance levels [7]

The PV panels are fabricated from the series-parallel arrangement of solar cells which are made up of semiconductor devices most commonly used of which is Silicon and Germanium. The solar cell converts the sunlight into the DC voltage. For an ideal scenario, the current drawn from the PV panel is given as[8].

$$I = I_L - I_O[\exp\left(\frac{qV}{nkT}\right) - 1] \tag{2.1}$$

Where I_L = Current generated due to solar light

q is the charge on an electron i.e. $1.6*10^{-19}$C

I_O = Saturation current

K is the Boltzmann's constant i.e. $1.38*10^{-23}$J/k

T is the cell operating temperature in Kelvin

In order to obtain maximum power from the PV panels, we need to operate it at a value of V_{mp} and I_{mp} since we know that the power is the product of current and voltage (P=V*I) as shown in figure 2-5. There needs to be attached a controller with the PV panel known as MPPT controller with a pertinent power electronics interface that is responsible for the utilization of maximum power from the PV panels all the time.

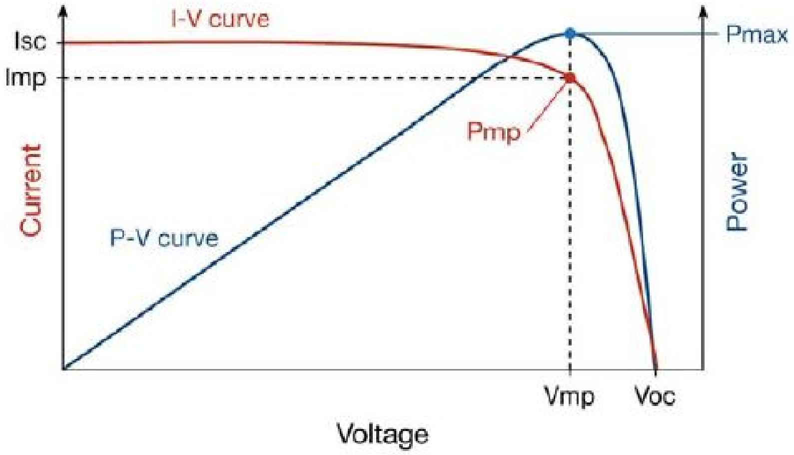

Figure 2-5: Power curve of PV module [9]

Some other points are also present on the power curve of a solar cell which are V_{oc} and I_{sc}. When the PV panel is operating at no load condition i.e. open circuited, the current from the PV cell is zero and voltage is at maximum value. This point is termed as open circuit voltage (V_{oc}). In a similar manner, when the terminals of the cell are short circuited, current attains the maximum value known as short circuit current (I_{sc}). The output power is maximum at neither of these points. Instead there is only point on a graph where we can get the maximum power all the time i.e. V_{mp} and I_{mp}.

2.2.2 Wind Energy Generation (WEG) System:-

Wind energy is also considered to be amongst the main renewable energy sources to replace the conventional fossil fuel based power plants. Frequent research is going out to use the wind energy as the major source of energy generation source because of its continuous availability, free from pollution and relatively low capital cost.

Wind energy generation systems can be categorized as fixed and variable speed wind turbines. VSWT are widely utilized due to the fact that speed of the wind is varying all over the day. So, in order to harness maximum energy from these systems, they are used practically in many of the available systems. Most commonly used topologies for these VSWT nowadays used are doubly-fed induction generators (DFIG) based wounded rotor, induction generators having squirrel cage rotors and permanent magnet synchronous generators commonly termed as PMSG [10-11]. PMSG based wind turbines are mostly used because of their lower failure rate, maximum power production and high reliability due to which they are used in onshore as well as off shore power generation systems [12].

Wind turbines normally operate by transforming the kinetic energy of the wind into the rotational kinetic energy of the turbine blades initially and then into the electrical energy that can be extracted using power electronics interfaced converters. The extracted power from the wind turbine is given as [13]

$$P = \frac{1}{2}\rho A V^3 k C_p \tag{2.2}$$

Where, P = output power in kW

C_p= maximum power coefficient (ideal value=0.59), also termed as Betz constant

A= swept area of the rotor turbine blades

ρ= density of air

V= speed of wind

k= 0.000133 (A constant to provide power in kilowatts)

The WEG systems consists of PMSG based wind turbine which converts the wind speed firstly into the rotation of turbine and then converting this rotational kinetic energy into the electrical energy using synchronous generator. A gear box is attached with the turbine so as to increase the speed of turbine. A MSC(machine side converter) works as a controlled rectifier and converts the AC voltage into the DC voltage which will vary in magnitude showing the variation in the speed of wind. A boost converter is used so as to step up this voltage whereas a GSC (grid side converter) is used as an inverter converting this DC voltage into an AC voltage. MSC is controlled for the purpose of magnetization and to build-up the reference torque [14-15]. Finally an LCL filter is used before connecting to grid so as to provide distortion less output as given in figure 2-6.

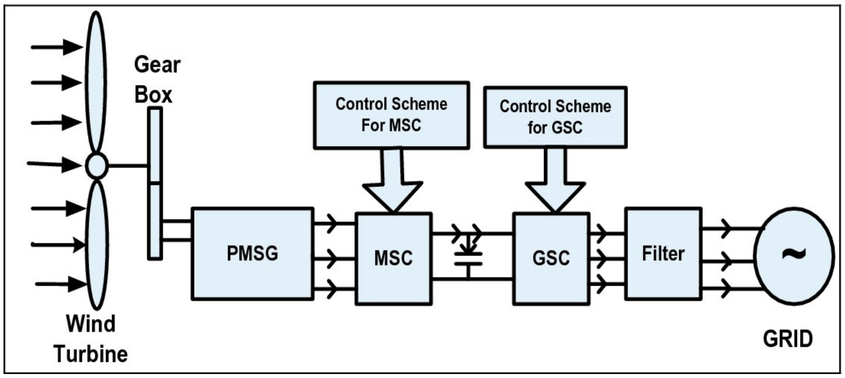

Figure 2-6: Grid connected PMSG based WEG system using back to back converters [16]

The problem that arises while considering WEG as a source of power generation systems is that a VSWT doesn't contribute to the system inertia due to reason that they are decoupled from the system through the use of power electronics based converters. This can result in decrease in system ability to cater to any frequency change in the event of any disturbance

2.2.3 Stability of a system:-

The stability of a system can be interpreted as the aptness of a system to retrieve its steady state when the system is exposed to any disturbance. The stability of power system can be categorized into 3 types

1. Transient stability
2. Steady state stability
3. Dynamic stability

2.2.3.1 Transient stability:-

Transient stability of a system can be termed as the strength of a power system to maintain its state of synchronism due to major disturbance in the operation of any parameter. These kinds of disturbances include tripping of a mega generator or a huge load due to a major fault in the system or due to any other factors.

2.2.3.2 Steady State stability:-

Steady state stability refers to the potential of a system to return to its steady state (original state) condition following gradual variations in the power system.

2.2.3.3 Dynamic stability:-

Dynamic stability of a system applies to the capability of the system to maintain its state of synchronism due to continuous small disturbances, such as variations in generation of power or load profile. It is also termed as "small-signal stability. This thesis focuses on the dynamic stability issues of PV-Wind hybrid system and the approach adopted to overcome these issues.

2.2.4 Frequency response of a system:-

Frequency response is supposed to be very essential in the operation of a power system because all the equipments are being designed keeping in view the operating frequency that varies from country to country. Frequency control is also used somewhere in place of frequency response. The frequency of a power system can be calculated using the equation 2.3

$$Frequency(f) = \frac{NP}{60} Hz \qquad (2.3)$$

Where N=speed of the generator in rpm

P = Generator number of poles

The frequency of the system decrements whenever the loss of generation occurs or increment in the load happens. The reason behind is that the generator will now take more energy to be able to cope up with the new increased load, causing the rpm of the generator to drop and according to the formula, the frequency drops. Similarly, the frequency of the system shoots up due to decrease in the load. The power fluctuation in both the scenarios is being delivered by ESS to keep the system frequency at the predefined steady state value.

ESS can participate both in primary as well as secondary control of frequency. The primary frequency controls can operate for some seconds until secondary frequency control actions can perform the back-up function which can serve for few minutes. To keep the balance between generation and load profile for controlling the frequency, various control actions are taken over a continuum of time. Figure 2-7 shows the frequency control actions being adopted for the power plants.

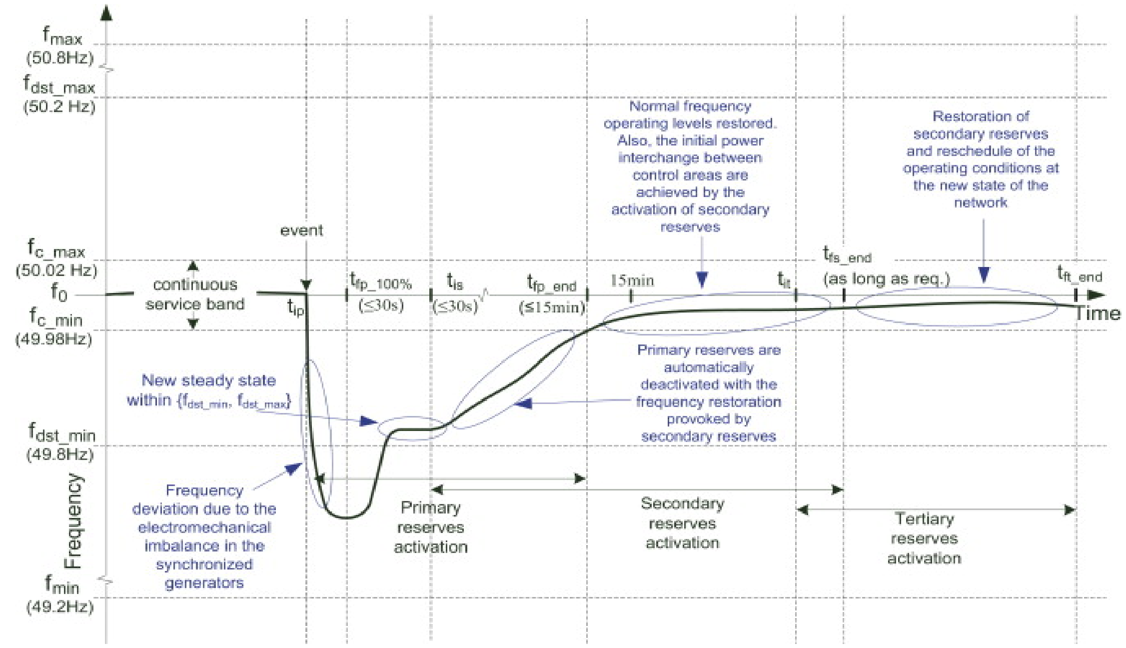

Figure 2-7: Frequency control action for power systems [17]

Whenever there is a variation in the power system frequency due to the imbalance between the generation and load behavior, the initial energy reserve of the power system plays its role to nullify the initial frequency deviation before the primary reserve comes in action and brings the system to its steady value. Conventionally, this is the task of huge masses of synchronous generators to provide the inertia in these kinds of events. Synchronous generators absorb or release kinetic energy to balance the mismatch. The rate at which energy is released or absorbed depends upon the ROCOF.

2.2.5 Rate of change of Frequency (ROCOF):-

The ROCOF, $\frac{d(\Delta f)}{dt}$ of a power system can be defined using a linear model of system frequency dynamics as[18]

$$\frac{d(\Delta f)}{dt} = \frac{f_o}{(2HS_b)}(\Delta P_m - \Delta P_{load}) \tag{2.4}$$

Where $\frac{d(\Delta f)}{dt}$ is the rate of frequency change, f_o is the nominal frequency of system, H is the inertia constant of the system, S_b is the apparent power rating of the power system, P_m is input mechanical power and P_{load} is the output electrical power. It is obvious from the equation that ROCOF of the system depends directly on the mismatch between the input mechanical power and the output electrical power. Also the ROCOF varies inversely to the inertial constant of the system. Lower the system inertia, higher will be the ROCOF and consequently the frequency deviation of system will be large causing instability and vice versa.

2.2.6 Boost Converter:-

It is used for stepping up the DC voltage level. Polarities of the input and output voltages are same. It has a single switch, a diode, a capacitor and an inductor as shown in figure 2-8. These converters have applications in electric vehicles, lighting systems and renewable energy integration.

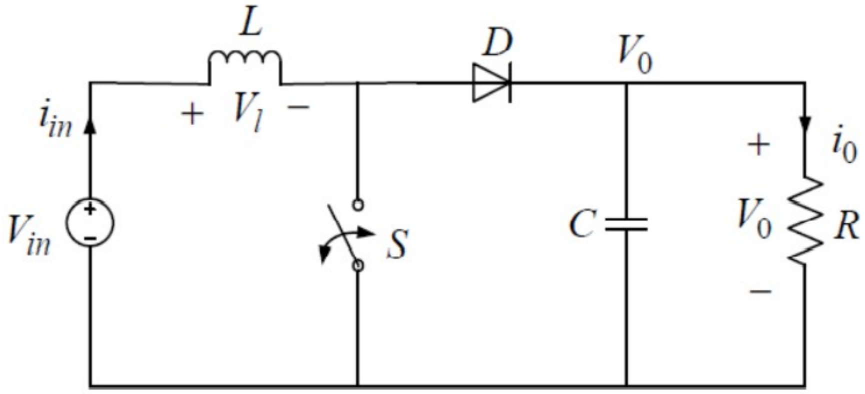

Figure 2-8: Circuit diagram of Boost converter [19]

It has 2 modes of operation. In mode I, the switch (S) is ON and the diode D is reverse biased. In mode II, the switch (S) is OFF while the diode D is in forward biased. The voltage gain of the boost converter can be written as equation 2.5

$$G_v = \frac{Vo}{Vin} = \frac{1}{1-D} \tag{2.5}$$

2.2.7 Voltage source inverter (VSI):-

A VSI can be interpreted as power electronics based converter which converts the input DC voltage into the symmetrical AC voltage of required frequency and magnitude. DC voltage is a constant value that is uncontrollable, but the AC voltage can be controlled. Pulse width modulation (PWM) is used to control the inverter's voltage and frequency. PWM technique regulates the on and off state of each switch in the inverter. A low pass filter (LC or LCL) is attached to the inverter's output so as to obtain a pure and distortion less sinusoidal AC output voltage.

Inverters are mainly categorized into two types: a) single phase inverter and b) three phase inverter. Inverters use electrical switches such as bipolar junction transistors

(BJTs), metal oxide semiconductor field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), and so on. The on-off pattern of these switches can control the inverter output's voltage.

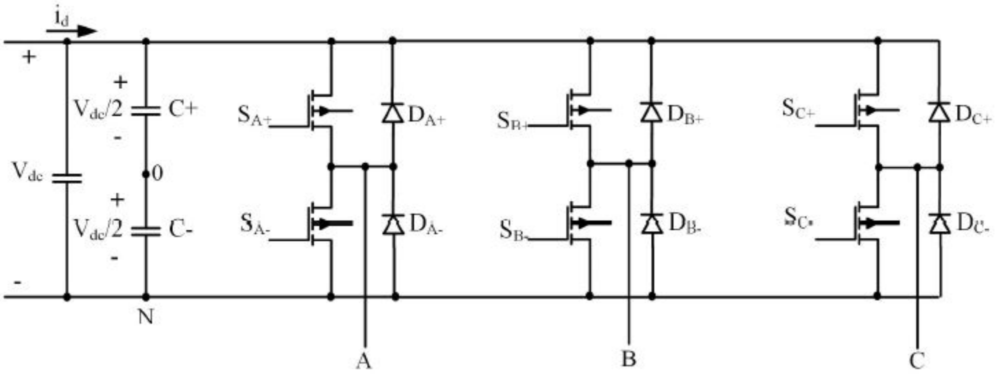

Figure 2-9: Circuit diagram of three phase PWM inverter [19]

The inverter used in this thesis is a three phase inverter which is used to convert the DC bus voltage from the hybrid energy sources (PV+Wind), thus providing an AC voltage which can be controlled. The inverter will function in a similar manner to a conventional synchronous generator and will provide the constant output voltage in the event of certain disturbances. Three phase PWM based inverters are provided with three leg switches one per phase as shown in figure 2-9.The switching signals are generated in a manner such that the output voltage produced by each phase is displaced from another by 120°.

2.3 Recently proposed topologies in literature:-

The transition from the conventional resources to distributed energy resources for the purpose of power generation is the demand of modern era, but this can lead to the deterioration of frequency which can cause the tripping of power supply in worst scenario. To address and to mitigate this issue, the researchers in the past few years are focusing to mimic the behavior of conventional synchronous generators mathematically by controlling the conventional inverter using pulse width modulation (PWM) technique. These newly designed systems are technically termed as virtual inertia (VI) based inverters.

There are various topologies that are proposed till now for the implementation of VI in the modern power systems. These topologies are based on various approaches adopted to bring the system to its nominal state under the condition of undesired fault. These topologies are presented in figure 2-10, some of which will be discussed briefly with their mathematical equations

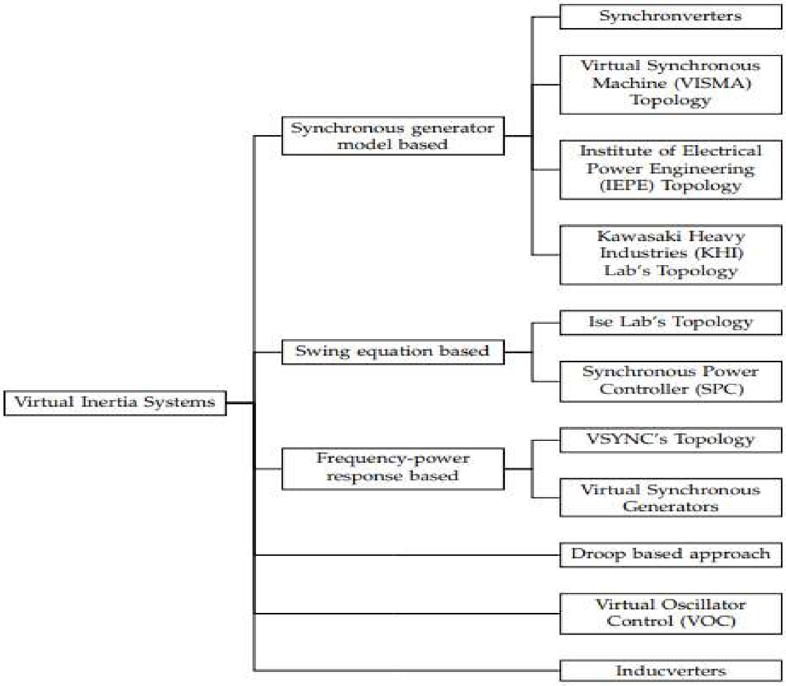

Figure 2-10: Different proposed VI emulation techniques [20]

2.3.1 Virtual Synchronous Generator (VSG):-

VSG is one of the techniques used for the purpose of VI emulation. This technique is composed of an ESS along with a power electronics interfaced component and a properly dispatched control algorithm that tends to behave like a SG to fulfill the short term energy storage requirements[21].

The energy storage material can be any DC source like batteries, flywheels or super-capacitors. In [22], a PLL is used to calculate the frequency of the system and also the ROCOF with the help of system voltage (V_{abc}). The control algorithm then calculates the power that needs to be injected into the system or absorbed from the system using the equation 2.6

$$P_{VSM} = K_D \Delta w + K_I \frac{d(\Delta w)}{dt} \tag{2.6}$$

Where

K_I is termed as the emulated inertia constant used to make the system perform during transient period to reduce the ROCOF.

K_D is the emulated damping constant used to bring the system frequency to a nominal value when any deviation in the frequency occurs.

Δw is the change in frequency and $\frac{d\Delta w}{dx}$ is the rate of change of frequency.

To calculate the values of K_I and K_D the formula are shown in equation 2.7 and 2.8

$$K_I = \frac{P_{VSG\_NOM}}{\frac{d(\Delta w)_{max}}{dt}} \tag{2.7}$$

$$K_D = \frac{P_{VSG\_NOM}}{(\Delta w)_{max}} \tag{2.8}$$

Where P_{VSM_NOM} is the nominal VSM power rating.

The controller based on the value of P_{vsg} generates the reference current signal for the controller provided by equation 2.9. The controller then according to the feedback current signal Ig(abc) generates the necessary gating signals for the voltage source inverter, thus exchanging the calculated active power between the microgrid and energy storage as shown in figure 2-11.

$$I_d = \frac{2}{3}\left(\frac{V_d P_{VSG} - V_q Q}{{V_d}^2 + {V_q}^2}\right) \tag{2.9}$$

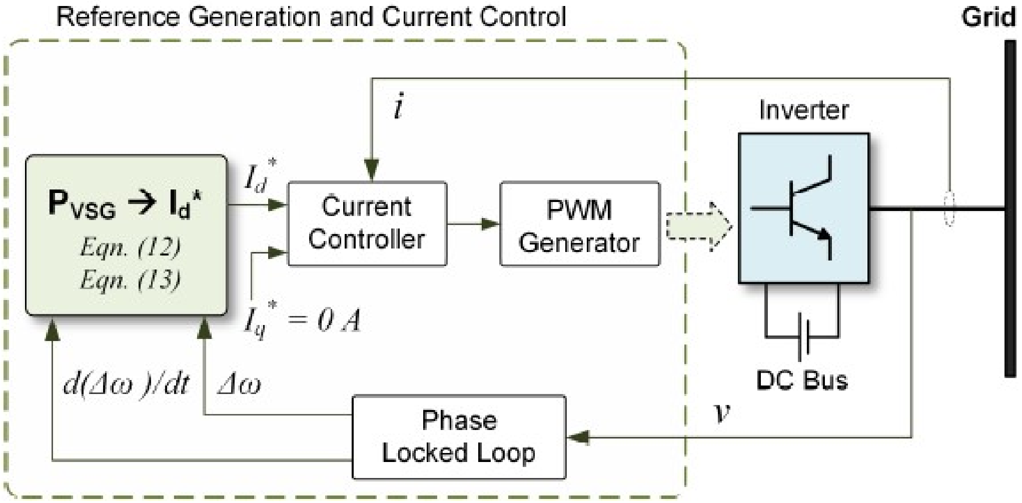

Figure 2-11: Virtual synchronous generator (VSG) topology [23]

2.3.2 Virtual synchronous machine (VISMA) Topology:-

Both VSM and VISMA are used as an abbreviation for virtual synchronous machines act as a commonly used technique for virtual inertia emulation. VSM technique was first proposed by Beck and Hesse in 2007 and was denoted as VISMA [24]. This technique operates by using *d-q*(synchronous reference frame) based mathematical model of a synchronous generator. Park transformation is used for converting a three phase (*abc*) signal to direct-quadrature-zero (*dq0*) rotating reference frame. This model uses the digital controller of an inverter thus replicating the dynamics of a SG. Real time grid voltage values are used to calculate the stator currents of the virtual machine which are injected based on a current control approach using a power inverter. The inverter is operated based on the PWM technique. The concerns regarding its applications include the numeric instability and the complexity in the PLL implementation. The VSM have some differences as compared to the proposed synchronverter topology. The inertia utilization range of VSM is larger, which eliminates the demand of DC link element or energy storage device[25], however the need of DC link element is necessary for the operation of synchronverter. The VSM control topology is shown in figure 2-12

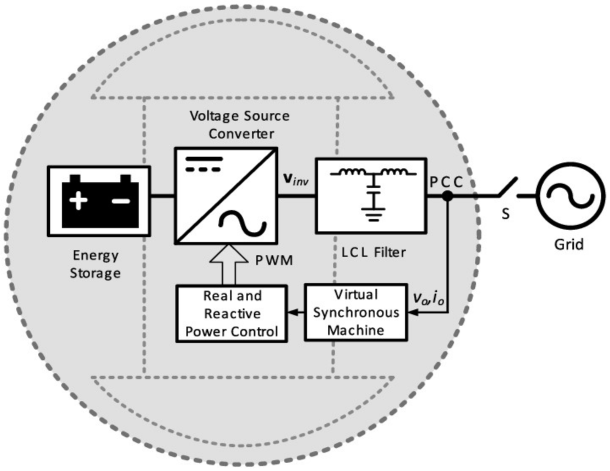

Figure 2-12: Virtual synchronous machine control topology [26]

2.3.3 IEPE's Topology:-

IEPE's topology is another proposed topology used for implementation of virtual inertia. This topology is based on implementing a dynamic model of a generator and then emulating its characteristics using a power inverter and an energy storage element [27] as shown in figure 2-13. The model anticipates either the reference current or voltage for the "Driver and pulse generator" block using the grid voltage or current respectively. The IEPE topology is better applied for islanded operation.

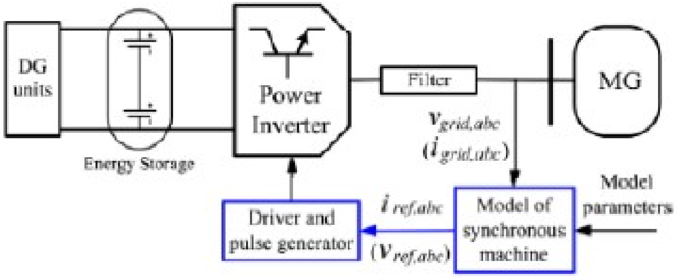

Figure 2-13: IEPE’s topology for virtual inertia emulation [27]

2.3.4 ISE Lab’s Topology:-

The technique proposed by ISE lab for emulation of virtual inertia implements swing equation based on the difference between the input and output power at the point of control logic [28]. The controller based on the inverter output current (*i)* and voltage (*v)* computes the frequency (*w_g)* and active output power of the inverter P_{out}. The controller based on the swing equation generates a phase signal θ for the PWM generator as shown in equation 2.10

$$P_{in} - P_{out} = J\Delta w \frac{d(\Delta w)}{dt} + D_p \Delta w \tag{2.10}$$

$$\Delta w = w - w_g$$

Where J and D_p represents the moment of inertia and damping coefficient respectively. The block diagram of the topology is shown in figure 2-14.

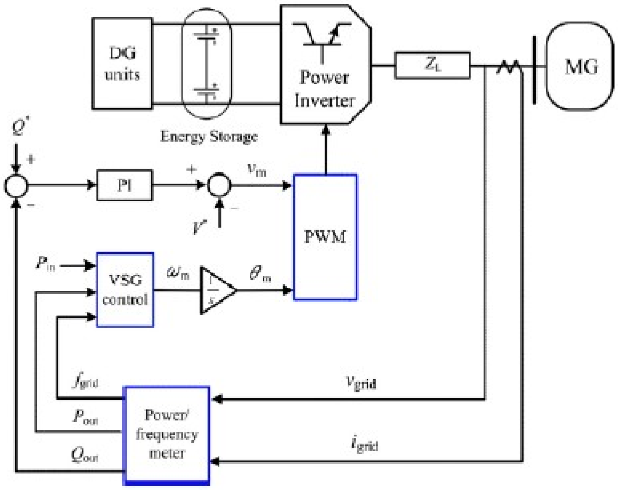

Figure 2-14: Block diagram for ISE Lab’s control topology for inertia emulation [28]

2.4 Proposed Topology (Synchronverter based inertia emulation):-

Synchronverters abbreviated as synchronous inverters are used for operating the inverter based RES presenting the same characteristics from the grid point of view [29]. The topology was presented very well by Q.C.Zhong [30]. Using synchronverter, a distributed generator or RES can be connected to the grid. A PLL is used for synchronizing the grid with the frequency and phase of inverter. A synchronverter is composed of 2 parts, power part or electrical part and the electronic part or the controller part. We can model a synchronverter as a combination of a power part which serves as an inverter to convert the DC signal to an AC signal along-with a control unit for regulating the operation of the inverter together with synchronization with the grid. This controller executes the mathematical model of a 3-phase round rotor synchronous machine. We will now discuss these parts separately along with their mathematical equations.

2.4.1 Power part (Electrical part):-

The power part of synchronverter can be represented by a DC-AC converter (inverter) to convert the DC voltage from RES into the three phase AC. It consists of three inverter legs that are operated using PWM technique and a combination of LC filters to suppress the ripples (voltage and current) during switching as shown in figure 2-15. The neutral line can also be added to the circuit if required. The power part of the system is the left part of the capacitors including the capacitors. The inductors denoted by L_g are not the part of the system but these can be used for synchronization and power control. Synchronverter is designed in order to preserve the nominal frequency, sustain its nominal voltage, perpetuate the difference between generated and consumed real power and to regulate the reactive power if connected to grid.

The terminal voltages of the synchronverter $[v_a \;\; v_b \;\; v_c]$ of the imaginary SG are represented as the capacitor voltages in figure 2-15. The impedance of the stator windings in case of SG are imaginary illustrated by inductance L_s and resistance R_s as shown in figure.

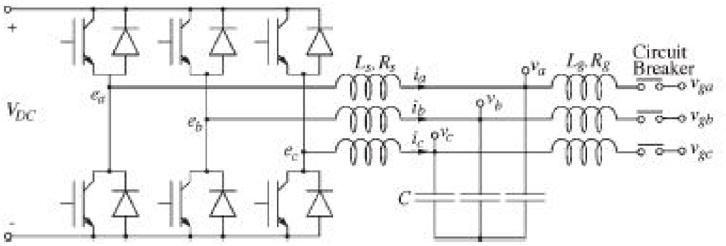

Figure 2-15: Power part of synchronverter [31]

The error signals denoted by [e_a e_b e_c] that arises due to the back EMF of imaginary rotor are the high frequency switching signals, the average of which over a switching period is equal to e. This error signal is fed to the inverter using the PWM technique. This signal can be represented mathematically by equation 2.11

$$e = \dot{\theta} M_f i_f \widetilde{sin\theta} \qquad (2.11)$$

Where M_f is the maximum value of mutual inductance between the stator & the rotor field coils and i_f is the field excitation current. $\dot{\theta}$ represents the machine virtual angular speed. sinθ can be defined as the 3 phase angle difference vector with equal spacing of 120° or 2π/3 in radian. This can be mathematically represented by equation 2.12

$$\widetilde{\sin\theta} = \begin{bmatrix} \sin\theta \\ \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \qquad (2.12)$$

2.4.2 Electronic part (Controller part):-

The DC bus voltage of the synchronverter needs to be constant. If not, a dc bus voltage controller in combination with an energy storage device is required to make it constant by regulating the flow of power in and out of the ESS. The electronic part of synchronverter operates under special program to control the switches as shown in figure 2-16. The controller part can be represented by mathematical model of a 3 phase round rotor synchronous machine. The equations that best describe the model of the machine are shown below. Equation (2.13) represents the droop in frequency that arises due to the difference between the mechanical and electrical torque generated.

$$\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p\dot{\theta}) \qquad (2.13)$$

Where J represents the moment of inertia, D_p is the damping factor. These parameters can be tuned for desired condition. T_m and T_e represents the mechanical and the electromagnetic torque. T_e can be calculated using the total energy available in the machine i.e. the sum of rotor and stator magnetic fields energy and the kinetic energy of the rotating part of the machine. Equation (2.14) represents the formula to calculate the electromagnetic torque.

$$T_e = M_f i_f \langle i, \widetilde{\sin\theta} \rangle \tag{2.14}$$

The real and reactive power that are generated from the inverter legs are given as

$$P = \langle i, e \rangle \quad , \quad Q = \langle i, e_q \rangle$$

The e_q is out of phase by e with a phase difference of π/2 i.e. from equation (2.11)

$$e_q = \dot{\theta} M_f i_f \widetilde{\sin\left(\theta - \frac{\pi}{2}\right)}$$

$$e_q = -\dot{\theta} M_f i_f \widetilde{\cos\theta} \tag{2.15}$$

So, the equations for the real and reactive power comes out to be

$$P = \dot{\theta} M_f i_f \langle i, \widetilde{\sin\theta} \rangle \tag{2.16}$$

$$Q = -\dot{\theta} M_f i_f \langle i, \widetilde{\cos\theta} \rangle \tag{2.17}$$

The $\widetilde{\cos\theta}$ can be mathematically represented as

$$\widetilde{\cos\theta} = \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}$$

All the parameters that are used in the equations are already discussed above. A PLL commonly termed as a phase locked loop is required to synchronize the inverter with the terminal voltage. This is required initially for the synchronization of power grid with the synchronverter. After that it is of no purpose. The use of a PLL has adverse effect on the performance of a weak grid since it can cause instability and negative impact on the performance of control system. Therefore the proposed controller is a self-synchronized which doesn't require PLL for synchronization to the grid. Certain changes are made to the basic synchronverter controller to operate it like a self-synchronized unit. These changes include adding a PI controller to adjust ΔT of frequency droop block and to equate D_p to zero. Secondly, a virtual current i_s that is generated due to the error between e and V_g and current injected to the controller can be either i_s or i_g[32]. The electronic/controller part of the synchronverter is show in figure 2-16.

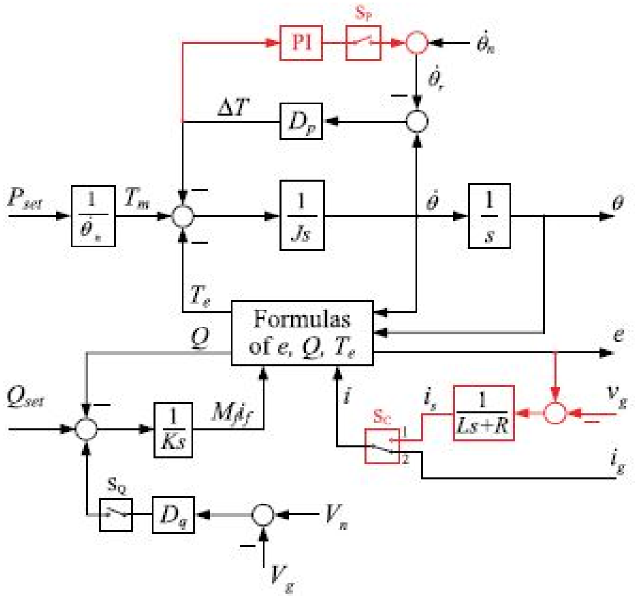

Figure 2-16: Electronic (controller) part of synchronverter with self synchronization unit [32]

The inverter output current (i) and grid voltage (v) are used for solving differential equations of the controller. The moment of inertia (J) and the damping coefficient (D_p) should be chosen according to the requirement because these value are crucial from the system stability point of view. The frequency and voltage loops are responsible for generating the inputs of the controller i.e. the mechanical torque (Tm) and $M_f i_f$ as shown in figure 2-16. In the frequency loop, Tm is generated by reference active power (P_{set}) depending upon the proposed angular frequency of the grid (θn). The virtual angular frequency of synchronverter (θ) is therefore generated by subtracting the two angular frequencies and passing the signal through an integrator and is used for the PWM signal. Similarly, in the voltage loop, the reference voltage (Vn) and the grid voltage (Vg) difference is multiplied by a voltage drooping constant (Dq). This signal is added to the error between the reference reactive power (Q_{set}) and the reactive power (Q) calculated using equation 2.17. The resulting signal is passed through an integrator with gain (K_v) to generate the field current signal$M_f i_f$. The controller outputs are e and θ which are used for PWM generation.

Summary:-

This chapter is being divided into four sections. The concept of inertia in conventional power systems and RES and the idea of virtually designed inertia is discussed in the first section.

The second section explains the working and operation of different components that are used for implementation of the proposed system. These includes the PV module characteristics curve, WEG system along-with the maximum power (Pm) that can be extracted from a wind turbine, concept of stability and frequency response of a system and different modules of the system that can constitute a system i.e. boost converters and voltage source inverters etc.

Third section covers recently proposed topologies that are used for the purpose of inertial emulation to the existing systems. The operation of various topologies along-with the mathematical expressions of some topologies is discussed briefly in the section. Finally the concept behind the proposed technology used in this thesis for the purpose of voltage and frequency support to the grid is covered in the last section

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Chapter 3: Methodology

In this chapter we will be going to analyze the procedures that are followed to achieve the objectives of the research. This chapter is divided into 4 parts. In the first part the MATLAB/SIMULINK software is used to implement the PV system while in the third part the implementation of WEG system is performed. Both the systems were designed using the fundamental blocks and the parameters of these systems are selected according to the parameters of the synchronous inverter. In the second part, the design and analysis of three phase synchronous inverter commonly known as synchronverter in SIMULINK is presented. The synchronverter functions like power electronics interfaced component consisting of 2 parts i.e. the power part and the electronics part (the control part). The control part is designed using the mathematical equations and these equations are then implemented in the software with the help of blocks to analyze the behavior of the system to regulate the real and reactive power, voltage and the frequency. Finally in the last part, a Hybrid energy system with a synchronverter control is modeled.

3.1 Development of 100kW, 500V PV system model:-

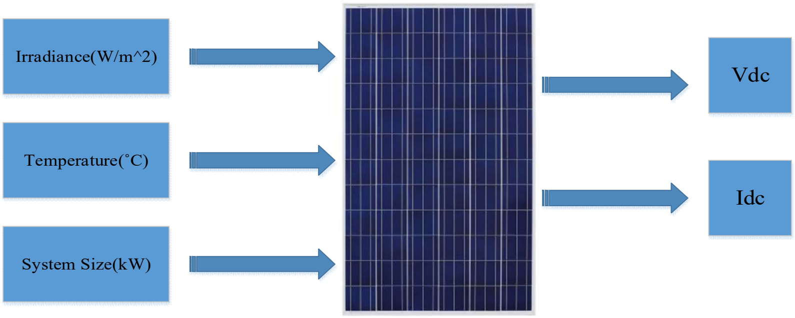


Figure 3-1: PV system model with inputs and outputs

The PV system with inputs and outputs is shown in figure 3-1. The three phase 100kW system is modeled using the in-built PV array block of the MATLAB/SIMULINK. The module selected is of 300W panel and a system of 66 parallel strings and 5 series modules per string. An LC filter is attached at the output so as to filter out the harmonics. The inputs to the model are the irradiance values (normalized to 1000 W/m^2) and the system is operated at a temperature of 25°C. The system parameters are presented in Table 3-1.

Table 3-1: PV system parameters

Parameters of PV System Model(330*Sunpower SPR 305E-WHT-D)			
Parameters	Symbol	Value	Unit
Number of series and parallel modules	Ns*Np	5*66	
Short circuit current of each panel	Isc	5.96	A
Open circuit voltage of each panel	Voc	64.2	V
Reference temperature	T_{ref}	25	°C
Solar irradiance	G	1000	W/m^2
Total power rating of system	P_{PV}	100	kW

The system voltage is then increased using a boost converter. The boost converter is a 5kHz DC-DC boost converter which will increase the PV voltage (from 273V DC at a maximum power) to 500V DC. The parameters of the DC converter are presented in Table 3-2.

Table 3-2: DC-DC boost converter parameters

Parameters of DC-DC Boost converter			
Parameters	Symbol	Value	Unit
Switching frequency of converter	f_s	5	kHz
Series inductance	L_{series}	5	mH
Shunt capacitance	C_{shunt}	10	mF
Series inductor resistance	R_i	0.005	Ω
Load resistance	R_L	2.48	Ω

The MATLAB/SIMULINK model of the PV system is shown in Figure 3-2.

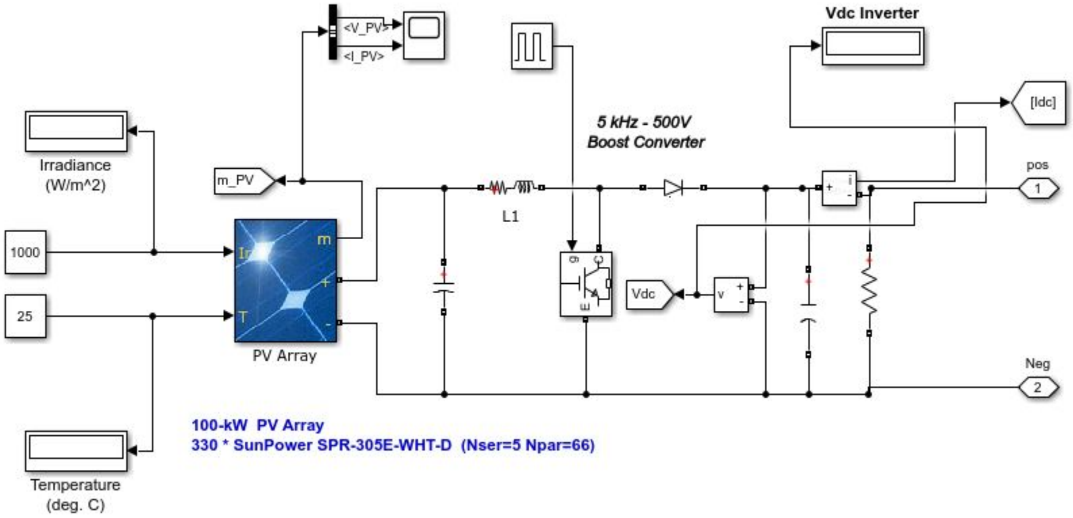


Figure 3-2: MATLAB/Simulink model of 100kW,500V PV system

3.2 Design and Analysis of Synchronverter Algorithm:-

Synchronverter can be termed as an inverter that can mimic the behavior of the synchronous generators. Just as the synchronous generators tends to protects the system in conventional power generation, Similarly, the integration of renewable power generators (specially the solar) requires a system that can operate in a similar manner as conventional synchronous generators or at least follow certain aspects of conventional power generators. As a result of this technique, the grid connected renewable energy resources (commonly known as distributed generation) can be able to take part in the regulation of frequency and voltage of the system.

The dynamic equations of synchronverter and synchronous generators are same. The difference in case of synchronverter is that the mechanical power is exchanged between the electrical part and the DC bus. This was supposed to be exchanged between the electrical and mechanical load (prime mover commonly) in synchronous generators.

3.2.1 Implementation of Synchronverter in MATLAB/SIMULINK:-

To implement the synchronverter in simulink, we will re-write the equations discussed in Chapter 2 for the sake of convenience

$$e = \dot{\theta} M_f i_f \widetilde{sin\theta}$$

$$\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p\dot{\theta})$$

$$T_e = M_f i_f \langle i, \widetilde{\sin\theta} \rangle$$

$$Q = -\dot{\theta} M_f i_f \langle i, \widetilde{\cos\theta} \rangle$$

These equations are modeled using the basic built-in MATLAB function block as shown in figure 3-3.

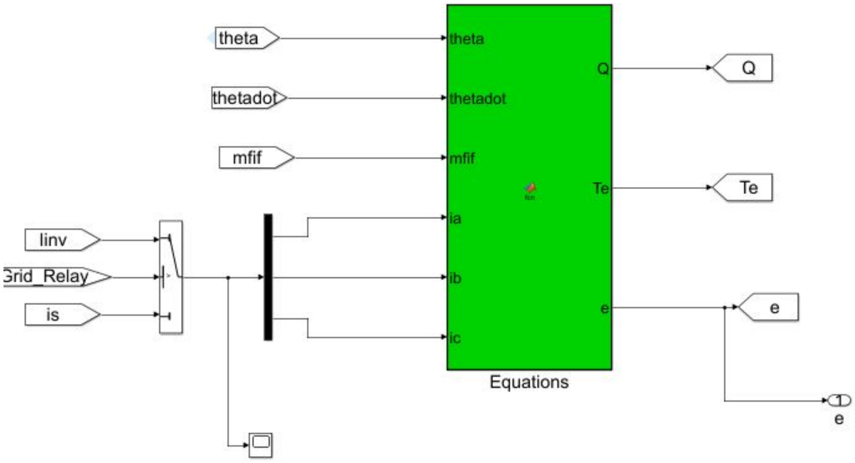
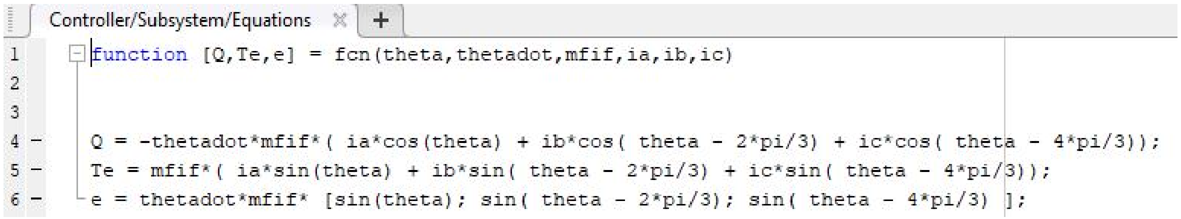


Figure 3-3: Equation block for synchronverter controller parameters

The m-file of the functions for calculating the parameters that includes the reactive power (Q), electromagnetic torque(T_e) and error signal(e) fed to the PWM generator is shown in figure 3-4.



```
function [Q,Te,e] = fcn(theta,thetadot,mfif,ia,ib,ic)


Q = -thetadot*mfif*( ia*cos(theta) + ib*cos( theta - 2*pi/3) + ic*cos( theta - 4*pi/3));
Te = mfif*( ia*sin(theta) + ib*sin( theta - 2*pi/3) + ic*sin( theta - 4*pi/3));
e = thetadot*mfif* [sin(theta); sin( theta - 2*pi/3); sin( theta - 4*pi/3) ];
```

Figure 3-4: M-file for calculating the controller signals

Since, the equations to implement the synchronverter controller are dependent upon certain parameters that include the rotor angle (θ), virtual angular speed of machine ($\dot{\theta}$), product of mutual inductance and stator field excitation current ($M_f i_f$) and virtual current (i_s). These parameters are modeled according to the proposed controller shown in figure 3-5 and 3-6.

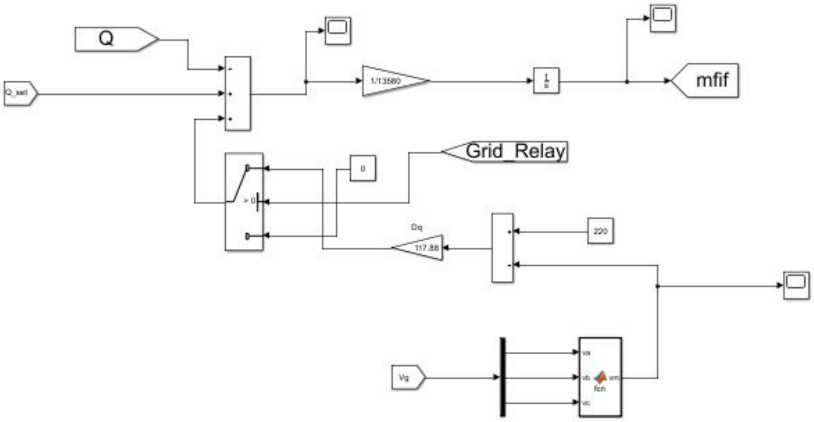


Figure 3-5: Simulink block diagram to calculate $\boldsymbol{M_f i_f}$

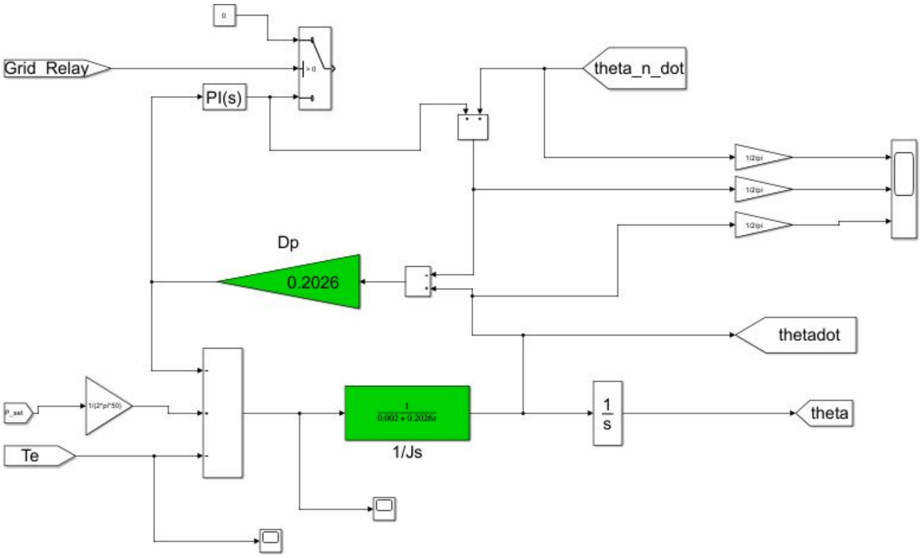


Figure 3-6: Simulink block diagram to calculate $\boldsymbol{\theta}$ ***and*** $\boldsymbol{\dot{\theta}}$

To mimic the function of connecting a physical machine to grid, a virtual per phase inductance (Ls+R) is used in order to connect the synchronverter to the grid. So the resulting current comes out to be i_s provided by the equation 3.1

$$i_s = \frac{1}{Ls+R}(e - V_g) \qquad (3.1)$$

This equation can be used to replace the grid current i_g by i_s for synchronverter to operate according to initial condition of P_{set}=0 and Q_{set}=0. The only difference is that a virtual current i_s is fed to the controller instead of grid current i_g. The values of L and R can be selected efficiently so as to speed up the process of synchronization. In the figure 3-7 voltage(e) is represented by V_{inv}. The parameters of the synchronverter are being provided in table 3-3

Table 3-3: Synchronverter parameters

Parameters of Synchronverter			
Parameters	Symbol	Value	Unit
Virtual per phase inductance	L	$0.2*10^{-3}$	H
Virtual per phase resistance	R	0.05	Ω
Nominal frequency	f_n	50	Hz
Proportional term	K_p	0.5	
Integral term	K_i	20	
Damping coefficient	D_p	0.2026	N.m
Actual inductance per phase	L_s	$0.45*10^{-3}$	H
Actual resistance per phase	R_s	0.135	Ω
Capacitance	C	$22*10^{-6}$	F
Dc link voltage	V_{dc}	500	V
Nominal voltage	V_n	220	V

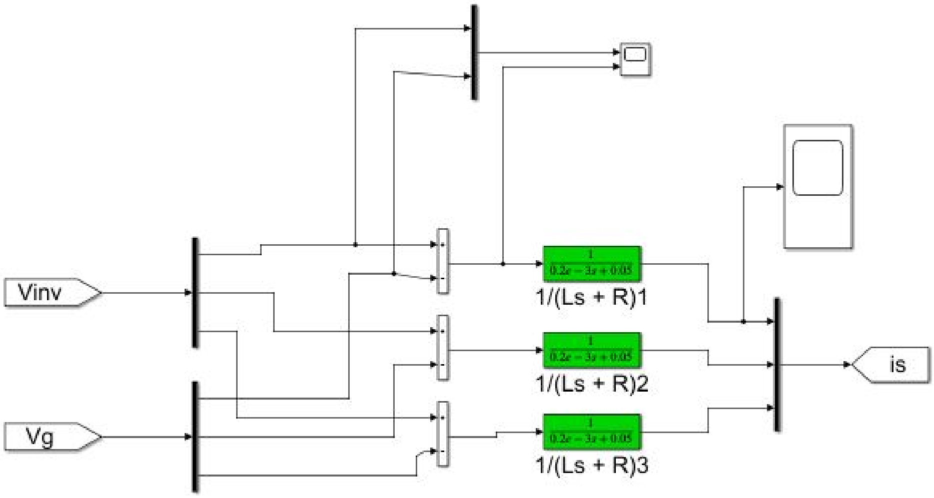


Figure 3-7: Simulink block diagram to calculate i_s

3.3 Development of 500V WEG System:-

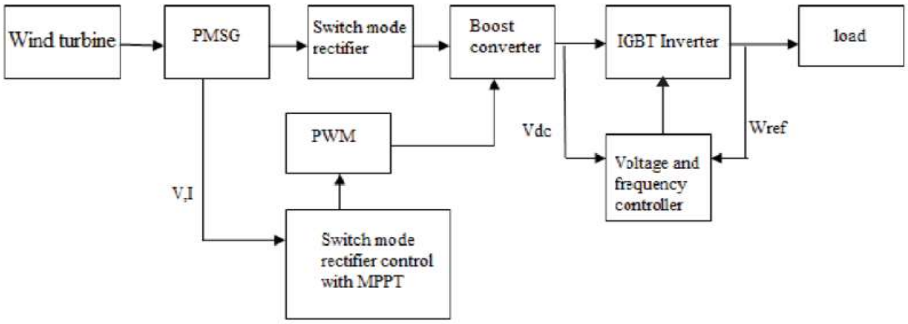


Figure 3-8: Block diagram of PMSG based VSWT with MPPT

The block diagram for PMSG based variable speed wind turbine in shown in figure 3-8. The WEG model consist of a PMSG based wind turbine along-with a DC-DC boost converter for converting the input voltage to 500V to synchronize the voltage of WEG with that of a PV system. To transfer the maximum power from wind turbine to the load (Grid), control algorithm is used. Generally, VSWT are used because of their operations for wider range of speeds. An advanced technique is designed to extract maximum power from wind turbine at all the speeds. The power P_w that can be obtained in a VSWT is a cubic function of the wind speed V_m[1] as shown in equation 3.2

$$P = \frac{1}{2}\rho\pi R^2 v^3 C_p \qquad (3.2)$$

All the parameters are being discussed in Chapter 2. C_p is the power coefficient that is dependent on the tip speed ratio λ and angle of blades β of the wind turbine. It can be represented as

$$\lambda = \frac{w_n R}{v} \qquad (3.3)$$

Where, w_n is the rotor speed of wind turbine. After substituting eq (3.3) to (3.2), and in order to achieve maximum values of C_p and P the optimal values of λ and β needs to be followed. The power can be considered as maximum power then denoted by P_m

$$P_m = K_{opt} {w_n}^3 \qquad (3.4)$$

Where $K_{opt} = \frac{1}{2}\rho\pi C_{pm}(\frac{R^5}{{\lambda_{opt}}^3})$. The base value of maximum power chosen here is 0.95. So the equation (3.4) becomes

$$P_m = 0.95 K_{opt} {w_n}^3 \qquad (3.5)$$

After consideration of the converter and PMSG ratings, the coefficient can be estimated by taking into consideration all possible value. This value can then be synchronverter to inject exact power into the grid. Because of the inbuilt capability of synchronverter, this scheme is able to cater the real power to the grid while regulating the reactive power. Different parameters of the system are shown in Table 3-4.

Table 3-4: WEG system parameters

Parameters of WEG System			
Parameters	Symbol	Value	Unit
Base wind speed	V_{wind}	12	m/s
Base rotor speed	V_r	1	p.u
Inertia of turbine	J	1.6	$kg.m^2$
Maximum power for base value of wind speed	P_{max}	0.9	p.u
Stator resistance per phase	R_s	0.425	Ω
Torque constants	T	3.2475	N.m
Nominal value of power coefficient	C_p	0.48	
Armature inductance	L_a	395	mH
Power rating of system	P	50	kW

The WEG system is connected to an energy storage system i.e. a Battery. The hybrid energy generation system (PV+Wind) along-with the battery needs to be attached to the DC bus at an approximately constant level. The energy storage system is used to keep the DC bus to a stable value. Thus, in the event of any misbalance between the generation and demand, this energy storage system is used to absorb the surplus power from the system and stores it for later use. Also it can inject the deficit power to the system when the system demand is more. The control of the battery needs to be performed so as to keep the battery voltage level in proportion to the DC bus level. The parameters of the battery are shown in Table 3-5.

Table 3-5: Battery parameters

Parameters of Energy Storage System (Battery)			
Battery type	Lithium-Ion		
Parameters	Symbol	Value	Unit
Nominal voltage	V_{nom}	500	V
Nominal rated capacity	C	6.5	Ah
Initial state of charge	SOC	60	%
Maximum charging current	I_{max}	90	A

The simulink block of WEG system with battery as an energy storage element is shown in figure 3-9.

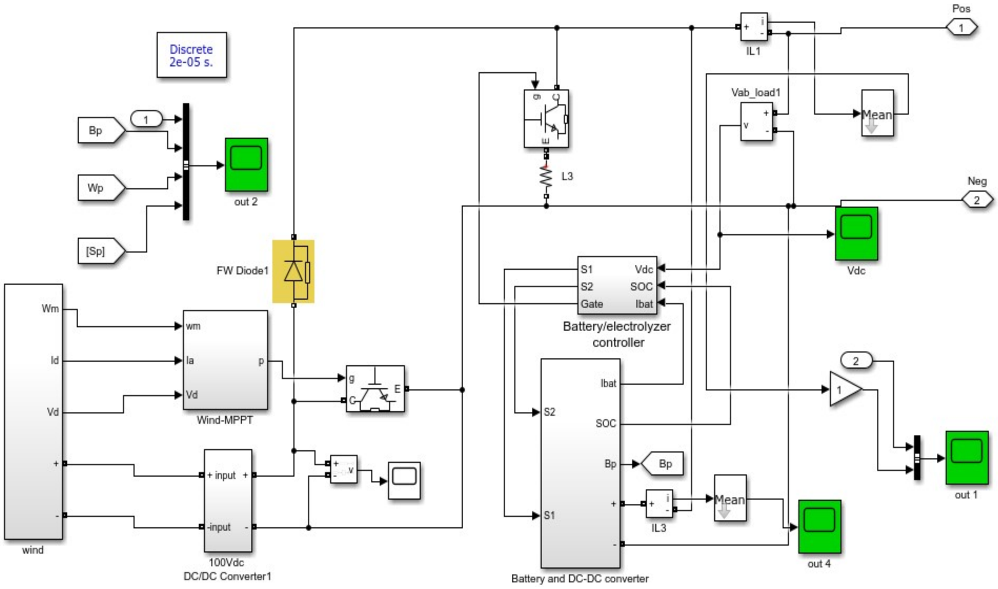


Figure 3-9: Simulink model of PMSG based WT and ESS model

3.4 Simulink model of synchronverter based hybrid power plant:-

The complete model of the hybrid energy generation system along-with the control of synchronverter is shown in figure 3-10. The system is connected to a three phase grid and the simulation is done to study the response of a system before and after connecting to the grid. The system is connected with the grid using a three phase circuit breaker and a step signal is used to connect the three phase grid with the system.

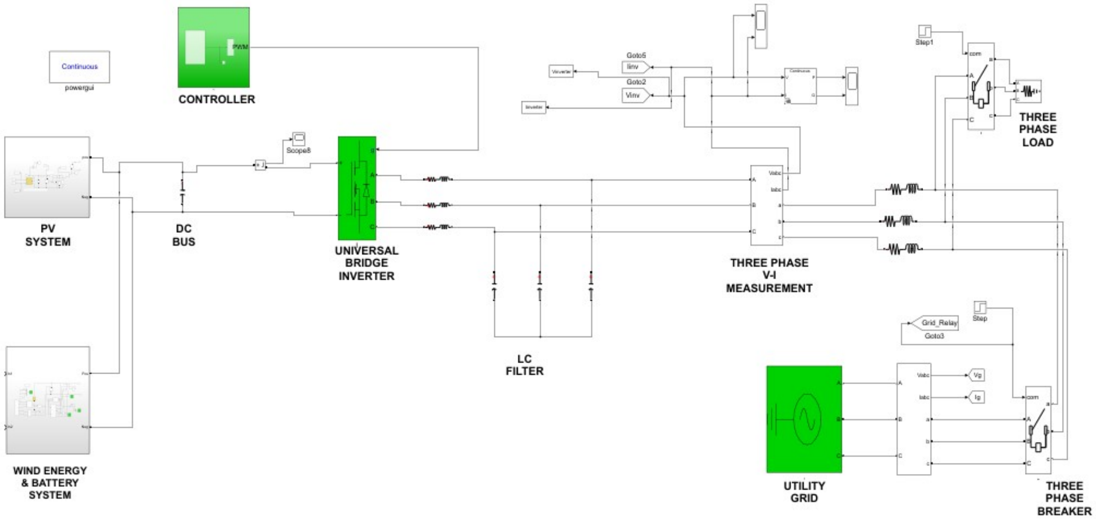


Figure 3-10: Simulink model of synchronverter controlled Hybrid power plant

Summary:-

This chapter provides the design process of synchronverter based virtual inertial control for hybrid power plants. The design of PV system is shown in the first part. The synchronverter is designed with the help of synchronous machine equations. The control part of synchronverter is then designed based on the block diagram shown in figure 11. Different parameters of the system are provided for proper functioning of the system. The design of WEG and battery control is also provided in the chapter.

In the last the subsystems are foregathered to design a Hybrid power plant with a capacitor acting as a DC bus and the virtual inertial control of system is developed using a synchronverter. The system is connected to a three phase to check the variation in system parameters before and after grid connection.

References:-

[1] Ma, Z., & Zhong, Q. C. (2012). Synchronverter-based control strategy for back-to-back converters in wind power applications. *IFAC Proceedings Volumes*, *45*(21), 349-354.

Chapter 4: Simulation Results and Discussion

The values for different parameters for various subsystems are already discussed in detail in Chapter 3. In this chapter we will be focusing on the implementation of proposed control strategy and verify the results with simulations carried out in MATLAB/SIMULINK. The parameters of the synchronverter provided in Table 3 are implemented for the verification of results. The damping coefficient for active power loop was chosen Dp=0.2026 in order to increase the active power for a frequency drop from nominal frequency. Similarly, the drooping coefficient for reactive power loop is selected Dq=117.88 to contribute the reactive power when the drop in the voltage occurs. The drop in frequency and voltage can be balanced based on the provision of active and reactive power based on the following equations.

$$\ddot{\theta} = \frac{1}{Js}(T_m - T_e - D_p(\dot{\theta}_n - \dot{\theta}_r) \qquad (4.1)$$

$$M_f i_f = \frac{1}{Ks}(Q_{set} - Q - D_q(V_n - V_g) \qquad (4.2)$$

Where $\ddot{\theta}$ represents the angular speed,$(\dot{\theta}_n - \dot{\theta}_r)$ represents the difference in angular speed between the nominal value and the actual value. The control parameters for the synchronverter are the T_m and $M_f i_f$. In order to operate the synchronverter, the controller is designed to generate these signals in a manner that system will ensure its stability. Since ($\omega = \dot{\theta} = 2\pi f$) , So the change in frequency from the nominal value will generate an error signal that is multiplied with the droop coefficient D_p. This frequency loop regulates $\dot{\theta}$ of the SG and creates the phase angle (θ) for the control signal (e) based on which the active power will be introduced to the system to bring the frequency back to its nominal value. Similarly, $(V_n - V_g)$ represents the difference between the nominal voltage and the grid voltage. So any change in voltage from reference value will generate the voltage error that is multiplied by Dq and then added to the error between Q_{set} and Q and the final signal is fed to an integrator with a gain of 1/K .Finally the reactive power to the system is provided by the field excitation current$M_f i_f$according to the value calculated by equation (4.2).

4.1 Effect on operating parameters for change in load (Load Increment):-

4.1.1 Change in Frequency:-

To study the response of the system parameters, the load on the system is changed. Performance analysis of a synchronverter due to variations in load is monitored and the time taken by synchronverter to bring the system to its nominal operating conditions in the event of sudden disturbance is analyzed. The simulation started at t=0 sec, and the system was loaded by 35kW at t=0.2 sec. This resulted in drop in system frequency from 50Hz to 49.5Hz. The synchronverter observed this disturbance and suddenly released the active power calculated according to the equation (4.1) to bring the frequency back to 50Hz. The time taken by synchronverter to cater this disturbance is less than 0.4sec as shown in Figure 4-1

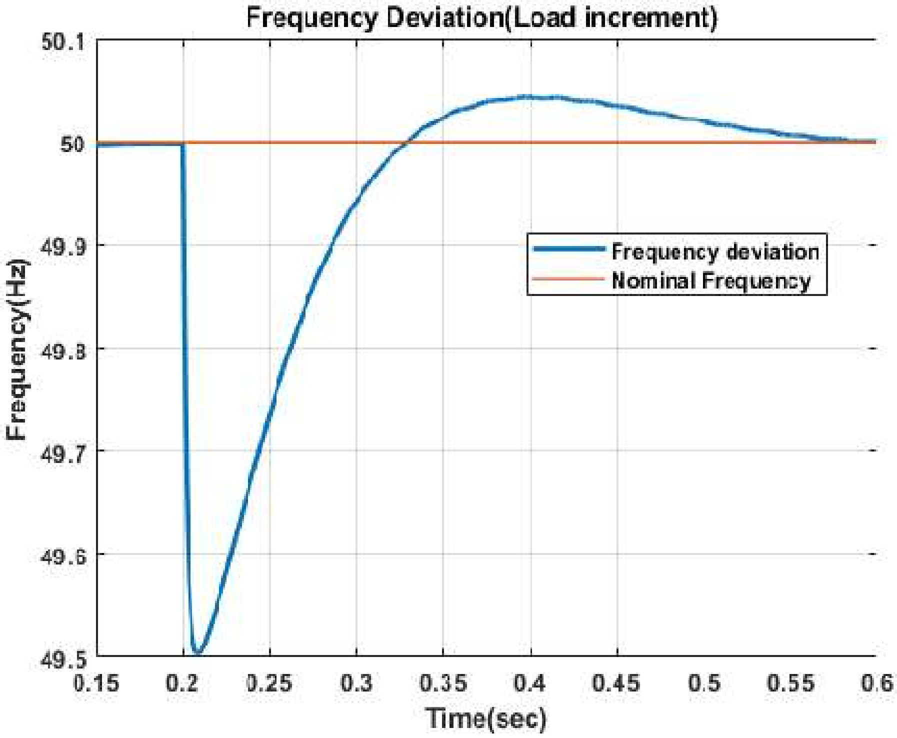


Figure 4-1: Change in frequency due to increase in load

4.1.2 Change in Current:-

The load increment caused an increased in the output current also. At t=0.2 sec the load current was increased to about 170A upto t=0.35 sec but this was because of transient current. The current soon achieved its steady state value of almost 140A at t=0.5 sec as shown in figure 4-2.

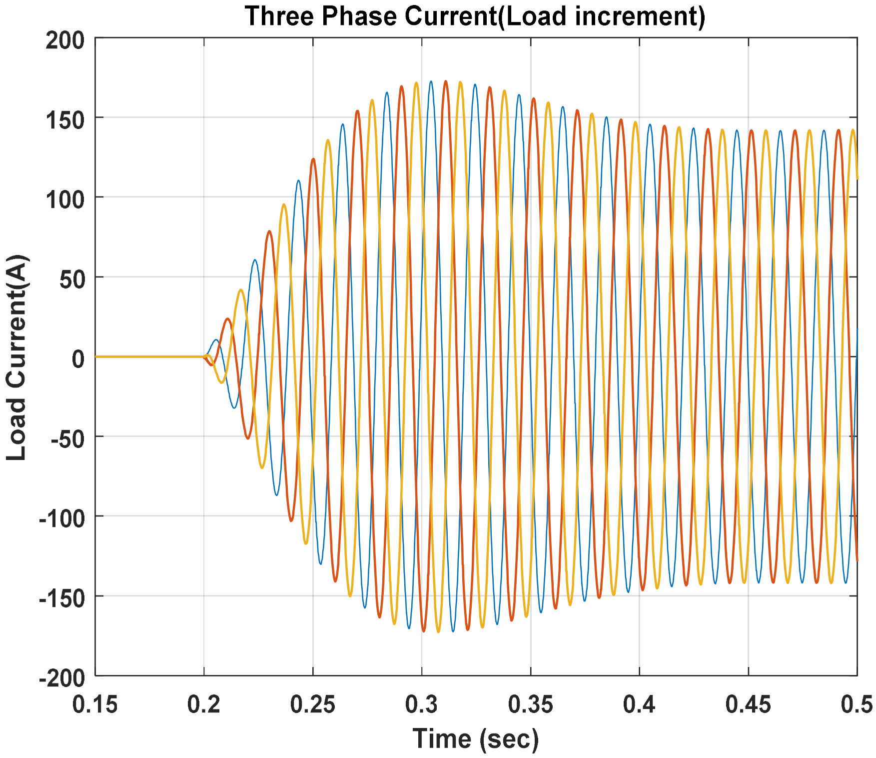


Figure 4-2: Change in current due to increase in load

4.1.3 Change in Voltage:-

It was observed that due to increase in load, all the parameters deviated from their original voltage except the voltage. The voltage of the system remained at its nominal operating value of 220V. This shows that due to an increase in active power demand from the system, the voltage remains unaffected as shown in figure 4-3

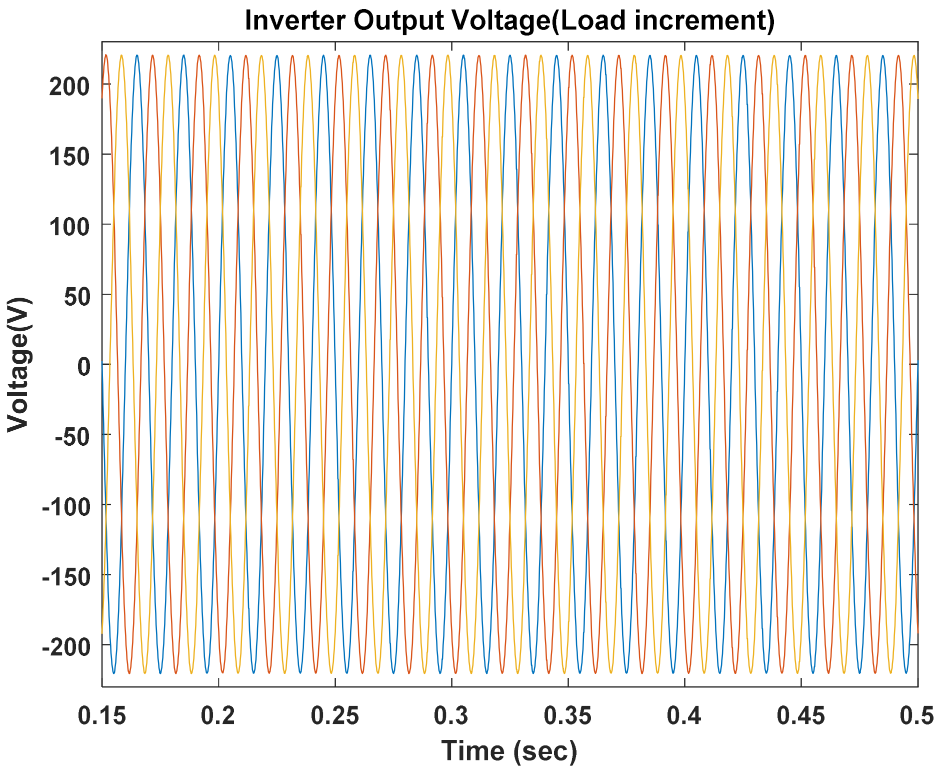


Figure 4-3: Voltage of the system due to increase in load

4.2 Effect on operating parameters for change in load (Load Decrement):-

4.2.1 Change in Frequency:-

To analyze the response of the system in the event of power imbalance between the generation and the demand, the load was decreased at t=0.6sec from 35kW to 15kW. The system frequency increases to 50.62Hz from its nominal value and brings an unwanted condition to the operation of the system. The synchronverter again comes in operation by absorbing the active power this time and attains the nominal value of the frequency in almost 0.3sec as shown in figure 4-4. The synchronverter tries to mimic the operation of synchronous generators that keeps the power imbalance to a minimum value by absorbing and releasing the active power due to the variation in the load.

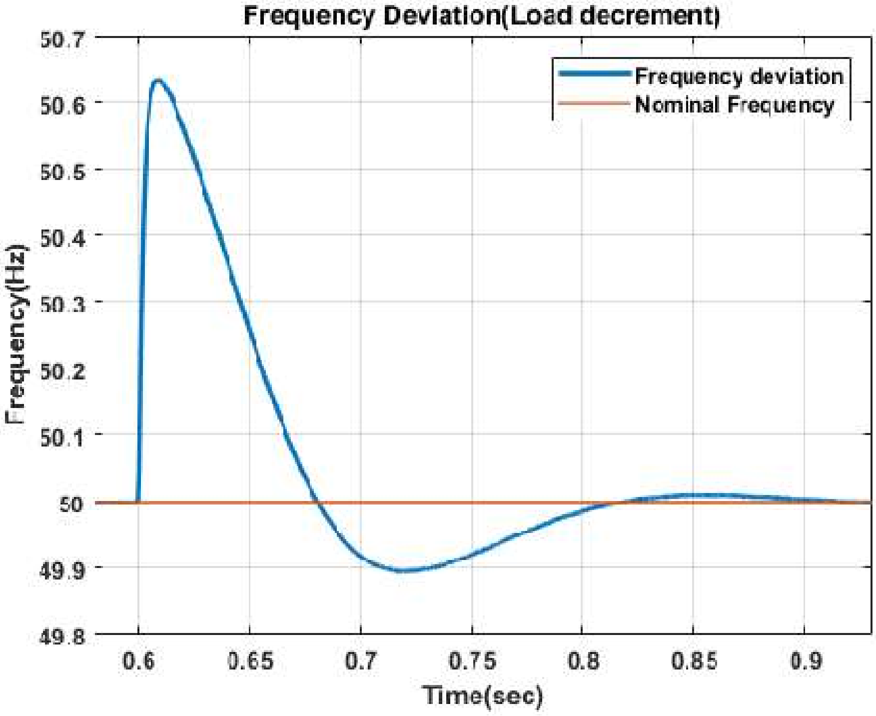


Figure 4-4: Change in frequency due to decrease in load

4.2.2 Change in Current:-

The load decrement also got reduction in the value of output load current. Due to the expulsion in the value of output power, it was observed that the load current started decreasing at the instant of loss of load at t=0.6 sec and it attained the steady state value of almost 75A at t=0.7sec as shown in figure 4-5.

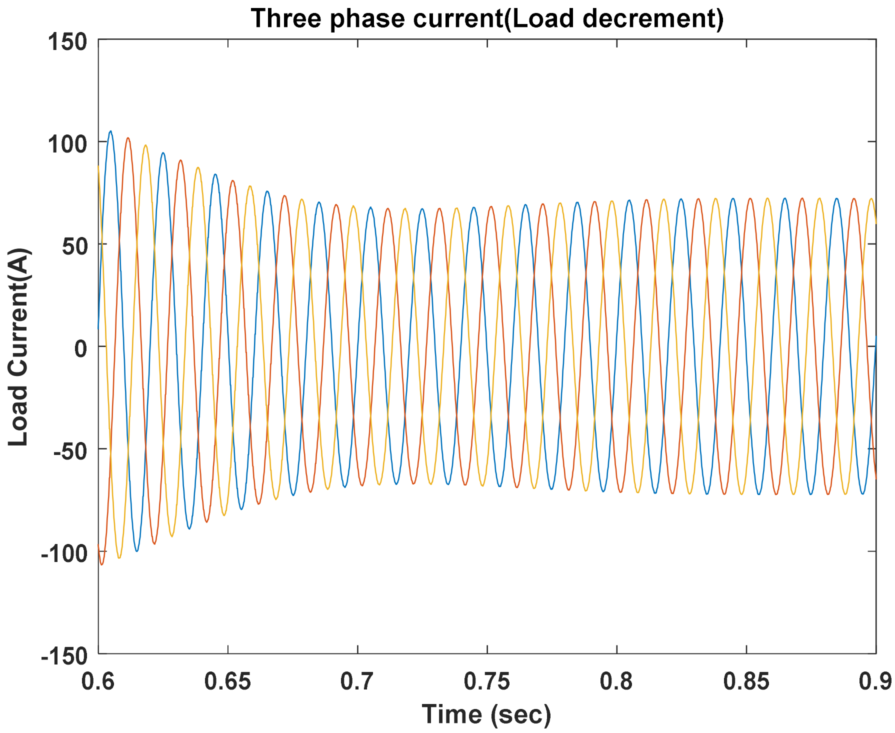


Figure 4-5: Change in current due to decrease in load

4.2.3 Change in Voltage:-

As discussed above, the voltage of the system maintained its nominal value of 220V even due to the decrement in load too. With decrease in the active power, frequency shoots up. So the system should be resilient enough to balance this condition by absorbing the additional power to the source thus bringing the frequency back to its supposed value in the minimum interval of time without affecting the voltage of the system. The system proposed in this research tries to perform this function as shown in figure 4-6.

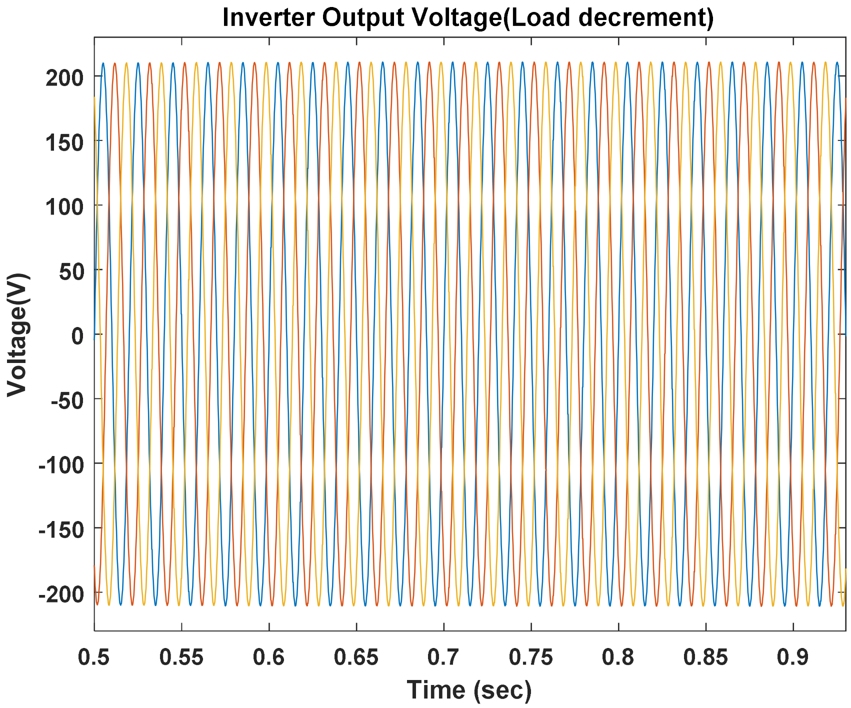


Figure 4-6: Voltage of the system due to decrease in load

4.3 Effect on System Voltage due to Reactive Power:-

4.3.1 Provision of reactive power:-

In order to analyze the response of the system voltage, the reactive power was provided to the system by applying a reactive load of 100kVAr to the system at t=0.3 sec. It was observed that the inverter voltage (having a nominal value of 220V) got a drastic increase at t=0.3sec. The system controller comes in action at the instant and releases the reactive power by regulating the $M_f i_f$ thus bringing the system back to its original value in less than 0.15sec as shown in the Figure 4-7.

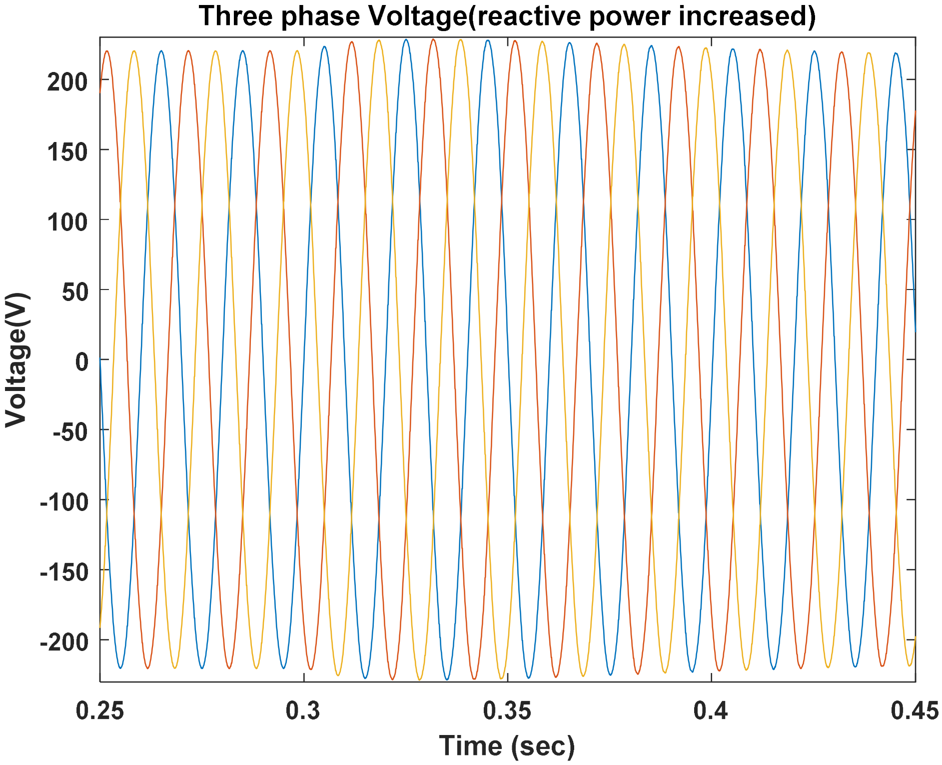


Figure 4-7: Change in voltage due to increase in reactive power

To verify the results properly the graph is zoom in only positive half of the waveform. The same results will be obeyed in negative half wave because this is a sine wave as shown in figure 4-8.

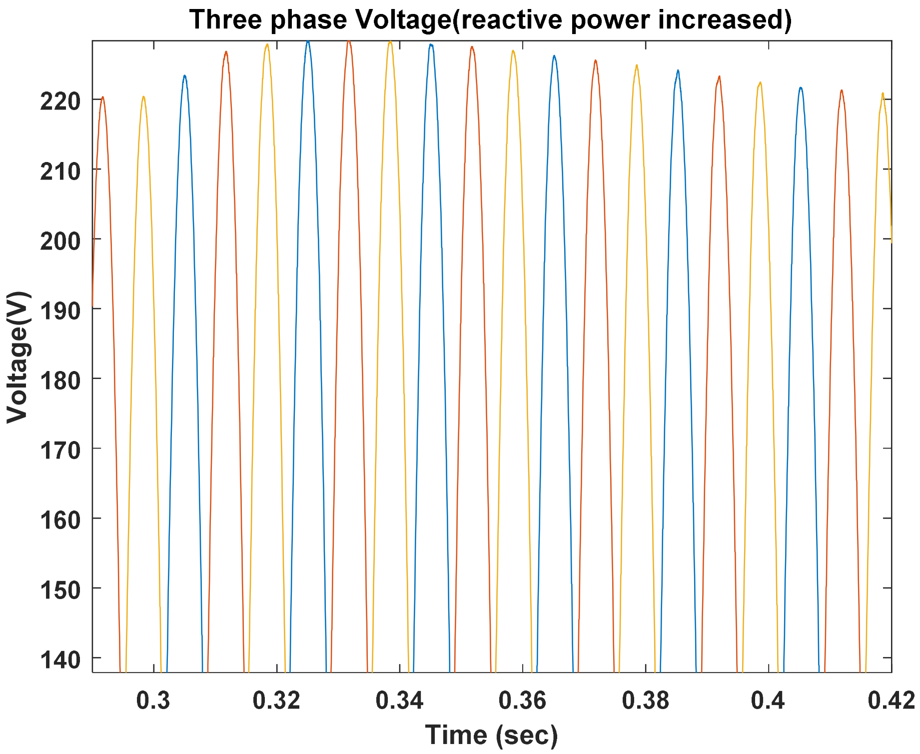


Figure 4-8: Zoomed version for verification of increase in voltage

4.3.1 Attenuation of reactive power:-

The load was decremented from its original value of 100kVAr to 30kVAr at t=0.7 sec. It was observed that due to decrease in load, the inverter voltage fall down to less than 200V (195V specifically). This condition was also judged by the synchronverter very quickly and the system voltage was restored to its original value in about 0.15 sec as shown in figure 4-8. This was done by regulating the value of $M_f i_f$.

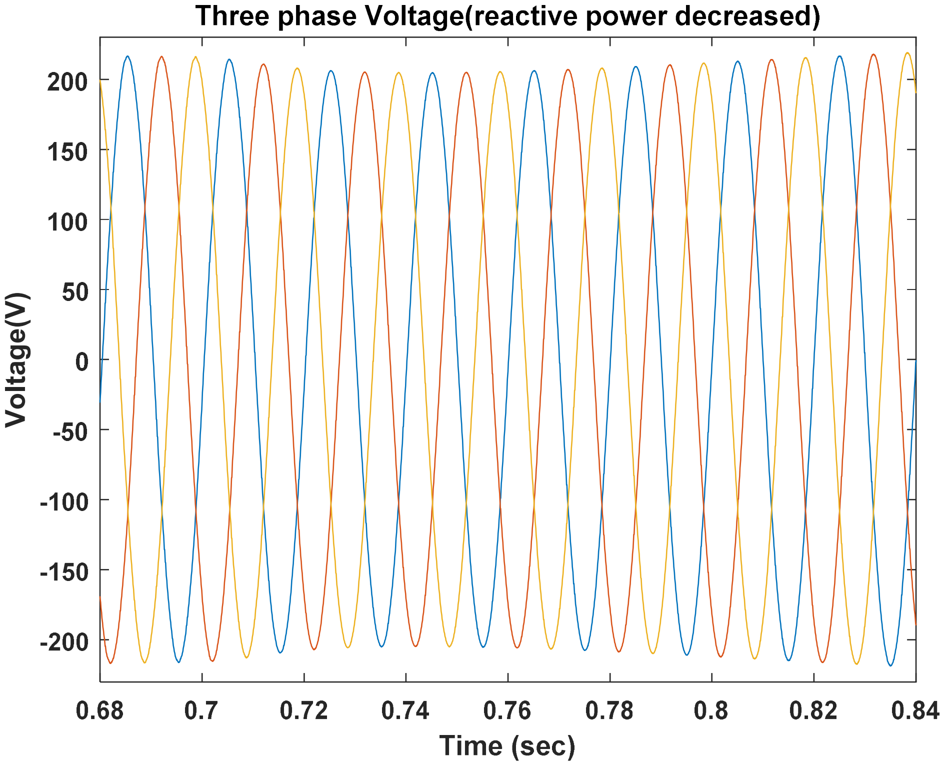


Figure 4-9: Change in voltage due to decrease in reactive power

SUMMARY:-

This chapter provides the simulation results for the synchronverter and its controlling mechanism at different operating conditions. The effect of the variation in the load on the graphs of the voltage, current, and the frequency are analyzed and the time required for the controller to come in action and to restore the nominal operating conditions of the parameters are discussed in this chapter. Also the effect of the reactive power inclusion on the voltage of the system is monitored and the control action of the synchronverter to maintain the constant voltage level at the output terminals of the inverter is being tracked. The synchronverter tries to balance out any sudden change in the system in the minimum interval of time which shows its nature of resiliency.

Chapter 5: Conclusion and Future Recommendations

In this thesis, we have modeled a 3 phase self-synchronized synchronverter which successfully imitated the grid frequency without the use of PLL. Since renewable energy systems (PV&Wind) are concerned majorly with the low moment of inertia due to absence of any moving parts in the former and the decoupled inertia from the main grid in the later resource. This can lead to the reduced resiliency of these systems when connected in islanded or grid connected mode in a microgrid. So an inverter is used to mimic the behavior of synchronous generator thus providing the support to the frequency and voltage droop behavior of these hybrid renewable energy resources in the event of sudden change in system parameters. The inverter synchronized itself with the grid very efficiently and whenever there was any deviation occurred in the frequency or voltage, it tracked those changes and restored them without any failure.

Thus it can be concluded that the synchronverter mimics the behavior in RES just like the synchronous generators in the conventional power plants. It is used to provide the inertia by the renewable energy resources to the transients in the grid.

The future recommendations for this research can be

- Design of a hardware prototype for such inverters to meet the locally used RES (most commonly PV) and to operate these resources in islanded as well as grid connected mode.
- The focus should be made on optimization of these inverters that can further increase their participation.
- A market based cost effective solution to ensure the availability of inertial services in future market of power devices.
- Deployment of inertia as a "service" to improve the power quality.