Stand - Alone Wind Energy Supply System Using Permanent Magnet Synchronous Generator

Udhayakumar P, Saravanan C, Lydia M

Abstract: Energy demand across the world is increasing and the resources are becoming scarce. The major source of power is from the conventional sources only. Some of the conventional sources of energies like thermal energy is produced from the fossil fuel coal which are depleting and is only limited to 2030. Renewable sources of energies are Solar, Wind, Biomass, etc hold bright prospect for the future. Wind industry has made rapid strides in the recent years. Wind power penetration has increased significantly in many interconnected power systems. Wind farms in remote places can also serve as stand – alone wind energy supply system. In this paper simulation of stand – alone wind energy supply system using permanent magnet synchronous generator is done.

Keywords: Permanent Magnet Synchronous Generator, Rectifier, Boost Converter, Voltage Source, PWM Inverter, Lead – Acid Battery.

I.INTRODUCTION

Renewable energy sources including wind power offer a feasible solution to distributed power generation for isolated communities where utility grids are not available. In such cases, stand-alone wind energy systems can be considered as an effective way to provide continuous power to electrical loads. One of the most promising applications of renewable energy generation lies in the development of power supply systems for remote communities that lack an economically feasible means of connecting to the main electrical grid. For isolated settlements located far from a utility grid, one practical approach to self-sufficient power generation involves using a wind turbine with battery storage to create a stand-alone system. Stand-alone wind energy systems often include batteries, because the available wind does not always produce the required quantities of power. If wind power exceeds the load demand, the surplus can be stored in the batteries[1]. The function of an electrical generator is providing a means for energy conversion between the mechanical torque from the wind rotor turbine, as the prime mover, and the local load or the electric grid.

The common types of AC generator that are possible candidates in modern wind turbine systems are as follows:

- Squirrel-Cage rotor Induction Generator (SCIG)
- Wound-Rotor Induction Generator(WRIG)
- Doubly-Fed Induction Generator(DFIG)
- Synchronous Generator (With external field excitation)
- Permanent Magnet Synchronous Generator(PMSG)

Most of them using Permanent Magnet Synchronous Generators in stand – alone Wind energy supply system.

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A control strategy of generator side converter and grid side converter to maintain the output of 3 Phase Voltage Source Inverter AC voltage as constant and the battery supply is to provide grid or utility purpose when the Wind Turbine is shutdown condition.

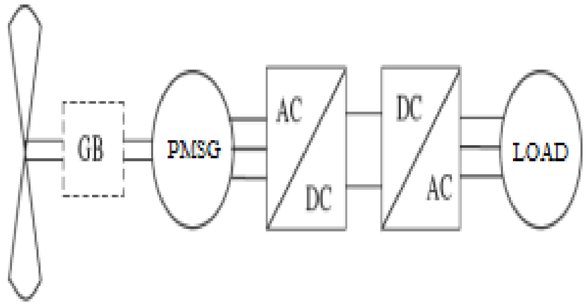

Fig. 1. Variable – Speed Wind Turbine with Synchronous Generator

The wind turbine is connected with the permanent magnet synchronous generator to extract electrical energy from wind in the form of KE – ME –EE. This electrical energy is fluctuating by the deviation of wind. Wind is not a constant wave. Diode rectifier is used to convert the PMSG output AC voltage into DC voltage. The rectifier filters are used to filter DC voltage and it is given to the inverter. The inverter is used to convert the DC voltage into constant AC voltage to connect with grid by using controllers. LC filters is used to filter and matching the inverter output AC voltage to grid.

II.WIND POWER

The first use of wind power was to sail ships in the Nile some 5000 years ago. The Europeans used it to grind grains and pump water in the 1700s and 1800s. The first windmill to generate electricity in the rural U.S.A. was installed in 1890 [5]. Today, large wind-power plants are competing with electric utilities in supplying economical clean power in many parts of the world.

The average turbine size of the wind installations has been 300 kW until the recent past. The newer machines of 500 to 1,000 kW capacity have been developed and are being installed.

Improved turbine designs and plant utilization have contributed to a decline in large-scale wind energy generation costs from 35 cents per kWh in 1980 to less than 5 cents per kWh in 1997 in favorable locations. At this price, wind energy has become one of the least-cost power sources. Major factors that have accelerated the wind-power technology development are as follows:

- High-strength fiber composites for constructing large.
- low-cost blades.
- Falling prices of the power electronics.

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- Variable-speed operation of electrical generators to capture maximum energy.
- Improved plant operation, pushing the availability up to 95 percent.
- Economy of scale, as the turbines and plants are getting larger in size.
- Accumulated field experience (the learning curve effect) improving the capacity factor.

III.ELECTRICITY GENERATION FROM WIND ENERGY

Wind energy technology has evolved rapidly over the last three decades with increasing rotor diameters and the use of sophisticated power electronics to allow operation at variable rotor speed [6]. Wind turbines produce electricity by using the power of the wind to drive an electrical generator. Wind passes over the blades, generating lift and exerting a turning force [4]. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700V to the appropriate voltage for the power collection system, typically 33 kV.

A wind turbine extracts kinetic energy from the swept area of the blades. The power in the airflow is given by,

$$P_{air} = \frac{1}{2}\rho A v^3 \qquad (1)$$

Where

ρ - air density (approximately 1.225 kg m^{-3}

A - swept area of rotor, m^2

v - upwind free wind speed, m s^{-1}

Although Eqn. (1) gives the power available in the wind the power transferred to the wind turbine rotor is reduced by the power coefficient, C_p:

$$C_p = \frac{P_{windturbine}}{P_{air}} \qquad (2)$$

Where,

C_p is the power coefficient

$$P_{windturbine} = C_p P_{air} = C_p \frac{1}{2}\rho A v^3 \qquad (3)$$

A maximum value of C_p is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum C_p values in the range 25–45%.

It is also conventional to define a tip-speed ratio λ, as

$$\lambda = \frac{\omega R}{v} \qquad (4)$$

Where,

ω rotational speed of rotor

R radius of tip of rotor

v upwind free wind speed, m s^{-1}

The tip-speed ratio λ, and the power coefficient, C_p, are dimensionless and so can be used to describe the performance of any size of wind turbine rotor. The maximum power coefficient is only achieved at a single tip-speed ratio and for a fixed rotational speed of the wind turbine this only occurs at a single wind speed. Hence, one argument for operating a wind turbine at variable rotational speed is that it is possible to operate at maximum C_p over a range of wind speeds.

IV.PMSG BASED WIND TURBINE GENERATING SYSTEM

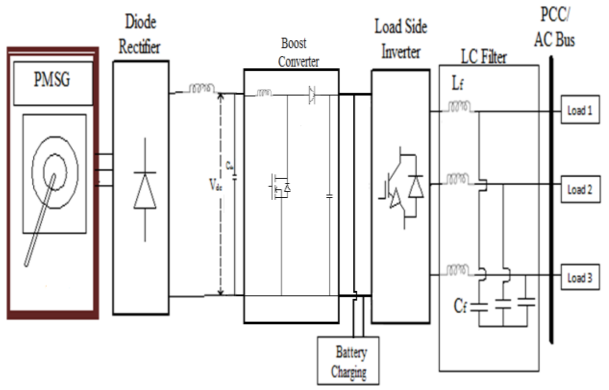

Fig. 2. Stand – alone wind energy supply system based on PMSG

In Fig. 2. the wind turbine is coupled with PMSG. When the wind is present, the turbine starts rotating which in turn gives the AC voltage. Using the diode rectifier AC voltage is converted into DC voltage. Then the DC voltage is stored in the battery using boost converter. After that the DC voltage is given to the load through the inverter.

Fig. 3. shows the simulink diagram of wind turbine generating system using PMSG. In the diagram it is shown that stator of the PMSG is connected to the battery charging system through power electronics converters[3]. Here generated power is converted to DC by using a diode rectifier. Output from the diode rectifier is connected to an inverter through an boost converter for improving the output voltage.

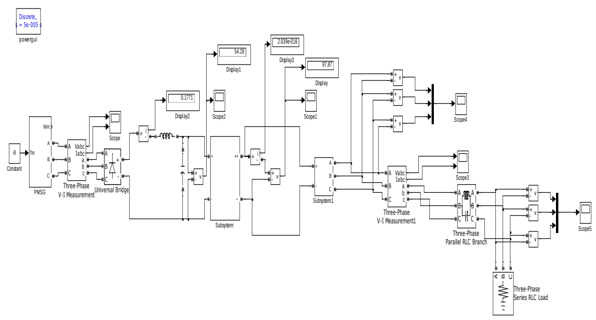

Fig. 3. Wind turbine generating system using PMSG

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Initially inverter is triggered by ordinary pulse generator with 180° mode of operation and simulation results are verified by analyzing THD of the output.

Then PWM inverter is used instead of ordinary inverter and the THD of output is analyzed.

A. Modeling of PMSG

The PMSG can be considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind. The dynamic model of the PMSG is derived from the two phase synchronous reference frame, in which the q-axis is 90°ahead of the d-axis with respect to the direction of rotation. Fig. 4. shows the *d-q* reference frame used in a PMSG, where θ is the mechanical angle, which is the angle between the rotor d-axis and the stator axis[2].

The mathematical model of the PMSG for power system and converter system analysis is usually based on the following assumptions: the stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor is concerned; the stator slots cause no appreciable variations of the rotor inductances with rotor position; magnetic hysteresis and saturation effects are negligible; the stator winding is symmetrical; damping windings are not considered; the capacitance of all the windings can be neglected and the resistances are constant (this means that power losses are considered constant).

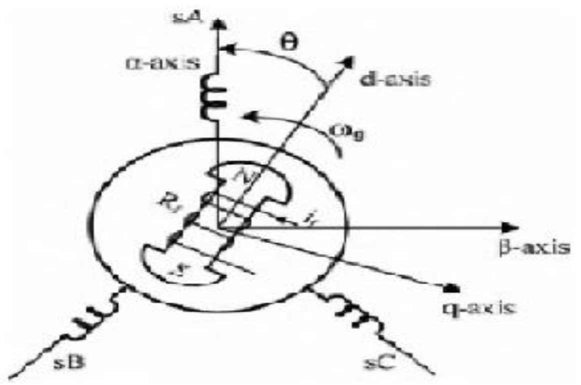

Fig. 4. $d-q$ and $\alpha-\beta$ axis of a typical PMSG

The mathematical model of the PMSG in the synchronous reference frame (in the state equation form) is given by,

$$\frac{di_d}{dt} = \frac{1}{L_{ds}} v_d - \frac{r_s}{L_{ds}} i_d + \frac{L_{qs}}{L_{ds}} \omega_e i_q \quad (5)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs}} v_q - \frac{r_s}{L_{qs}} i_q - \frac{L_{ds}}{L_{qs}} \omega_e i_d - \frac{\psi_f \omega_e}{L_{qs}} \quad (6)$$

Where,

$\frac{v_d}{i_d}$ d – axis voltage(V)/current(A)

$\frac{v_q}{i_q}$ q – axis voltage(V)/current(A)

r_s stator resistance(Ω)

L_{ds} stator d – axis inductance(H)

L_{qs} stator q – axis inductance(H)

ψ_f permanent magnetic flux(Wb)

ω_e electrical speed(rad/s)

$$\omega_e = p\omega_m \quad (7)$$

Where,

p pole pairs

ω_m mechanical speed(rad/s)

$$T_e = 1.5p((L_{ds} - L_{qs})i_d i_q + i_q \psi_f \quad (8)$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - F\omega_m - T_m) \quad (9)$$

Where,

J combined inertia of load and rotor(kg-m^2)

F combined viscous friction of load and rotor(Nm-s)

T_m shaft mechanical torque(N-m)

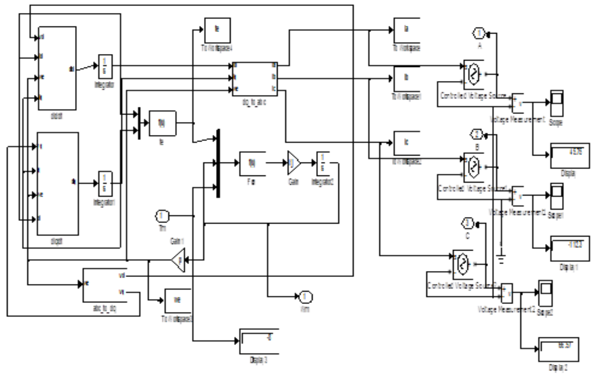

Fig. 5. Modeling of PMSG

Fig. 5. shows the modeling of PMSG. In which constant torque is given, i.e, assumed that input wind speed is constant.

B. Modeling of Battery

Batteries accumulate excess energy created by the wind energy system and store it to be used when there is no other energy input. Batteries can discharge rapidly and yield more current that the charging source can produce by itself, so pumps or motors can be run intermittently. Different chemicals can be combined to make batteries. Some combinations are low cost but low power also, others can store huge power at huge prices. Lead-acid batteries offer the best balance of capacity per dollar and it's a common battery used in stand-alone power systems.

The lead-acid battery cell consists of positive and negative lead plates of different composition suspended in a sulfuric acid solution called electrolyte.

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When cells discharge, sulfur molecules from the electrolyte bond with the lead plates and releases electrons.

When the cell recharges, excess electrons go back to the electrolyte. A battery develops voltage from this chemical reaction. Electricity is the flow of electrons. In a typical lead-acid battery, the voltage is approximately 2 volts per cell regardless of cell size. Electricity flows from the battery as soon as there is a circuit between the positive and negative terminals. This happens when any load (appliance) that needs electricity is connected to the battery.

The battery design equations are given by,

$$V_{bat} = V_1 + I_{bat} R_1 \quad (10)$$

$$R_1 = R_{ch} = \left(0.758 + \frac{0.139}{[1.06 - SOC(t)]n_s}\right)\frac{1}{SOC_m} \quad (11)$$

$$V_1 = V_{ch} = [2 + 0.148 SOC(t)]n_s \quad (12)$$

$$R_1 = R_{dch} = \left(0.19 + \frac{0.1037}{[SOC(t) - 0.14]n_s}\right)\frac{1}{SOC_m} \quad (13)$$

$$V_1 = V_{dch} = [1.926 + 0.124 SOC(t)]n_s \quad (14)$$

$$SOC(t+dt) = SOC(t)\left(1 - \frac{Ddt}{3600}\right) + \frac{K_b\left(V_{bat} I_{bat} - R_1 I_{bat}^2\right)dt}{3600} \quad (15)$$

$$SOC(t) = SOC(t-1) + \frac{1}{3600}\int_{t-1}^{t}\left[\frac{K_b V_1 I_{bat}}{SOC_m} - SOC(t-1)D\right]dt \quad (16)$$

Where,

V_{ch} is the battery charging voltage

V_{dch} is the battery discharging voltage

R_{ch} is the battery charging resistance

R_{dch} is the battery discharging resistance

SOC_1 is the initial state of charge

$SOC(\%)$ is the available charge

SOC_m is the maximum state of charge

n_s is the number of $2V$ cells in series

$D(h^{-1})$ is the self discharge rate of battery

K_b (no unit) is the charging and discharging battery efficiency

The battery charging circuit has been modeled in Fig.6.

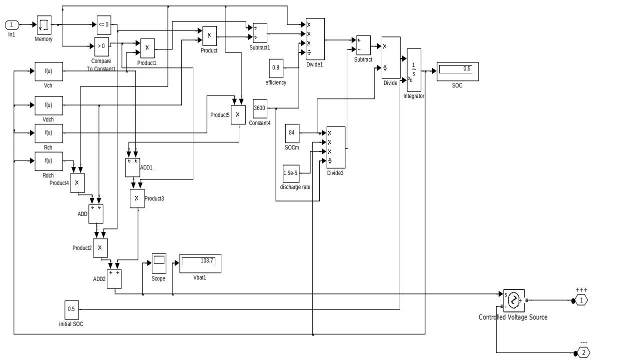

Fig. 6. Battery charging circuit

V.POWER ELECTRONICS FOR PMSG BASED WTGS

A. Rectifier

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as rectification.

For three-phase AC six diodes are used. Double diodes in series, with the anode of the first diode connected to the cathode of the second, are manufactured as a single component for this purpose. Some commercially available double diodes have all four terminals available so the user can configure them for single-phase split supply use, half a bridge, or three-phase rectifier. Many devices that generate alternating current (some such devices are called alternators) generate three-phase AC. For a three-phase full-wave rectifier with ideal thyristors, the average output voltage is

$$V_{dc} = V_{av} = \frac{\sqrt[3]{3V_{peak}}}{\pi}\cos\alpha \quad (17)$$

Where,

V_{dc}, V_{av} – the DC or average output voltage,

V_{peak} – the peak value of the phase input voltages,

π = ~ 3.14159

α = firing angle of the thyristor (0 if diodes are used to perform rectification)

B. Three phase inverter

Three-phase inverters are used for variable-frequency drive applications and for high power applications such as HVDC power transmission. A basic three-phase inverter consists of three single-phase inverter switches each connected to one of the three load terminals. For the most basic control scheme, the operation of the three switches is coordinated so that one switch operates at each 60 degree point of the fundamental output waveform. This creates a line-to-line output waveform that has six steps. The six-step waveform has a zero-voltage step between the positive and negative sections of the square-wave such that the harmonics that are multiples of three are eliminated as described above.

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When carrier-based PWM techniques are applied to six-step waveforms, the basic overall shape, or envelope, of the waveform is retained so that the 3rd harmonic and its multiples are cancelled.

To construct inverters with higher power ratings, two six-step three-phase inverters can be connected in parallel for a higher current rating or in series for a higher voltage rating. In either case, the output waveforms are phase shifted to obtain a 12-step waveform. If additional inverters are combined, an 18-step inverter is obtained with three inverters etc. Although inverters are usually combined for the purpose of achieving increased voltage or current ratings, the quality of the waveform is improved as well.

C. Boost converter

A boost converter (step-up converter) is a DC-to-DC power converter with an output voltage greater than its input voltage. It is a class of switched-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple.

$$V_o = \frac{V_i}{1-D} \qquad (18)$$

Where,

V_o is the output voltage

V_i is the input voltage

D is the duty cycle

D. Filters

A rectifier should provide an output voltage that should be as smooth as possible. In practice, however, output voltage from rectifier consists of dc component plus ac component or ac ripples. The ac component is made up of several dominant harmonics. AC ripples in rectifier output current do not contribute to motor torque, or to the energy stored in the battery. AC component merely causes more ohmic losses in the circuit leading to reduced efficiency of the system. This shows that it is of paramount importance to filter out the unwanted ac component present in the rectifier output. For this purpose, filters are used. When used on the rectifier output side, these are called dc filters; these tend to make the dc output voltage and current as level as possible. The more common dc filters are of L, C and LC.

VI. SIMULATION RESULT

This paper deals with simulation of stand – alone Wind Turbine Generating System (WTGS) using PMSG. The circuit can be used for two purposes: firstly the output of the inverter can be used to supply ac loads and the output of the rectifier can be used for battery charging applications.

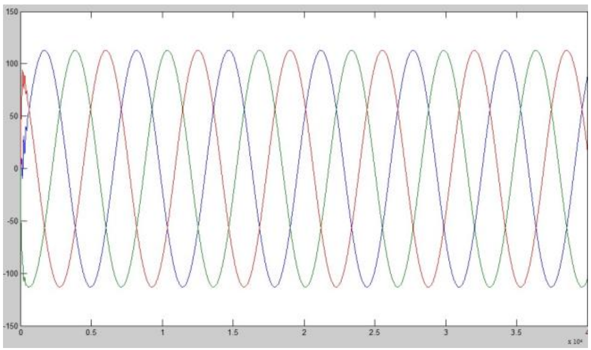

Fig. 7. Output voltage of PMSG

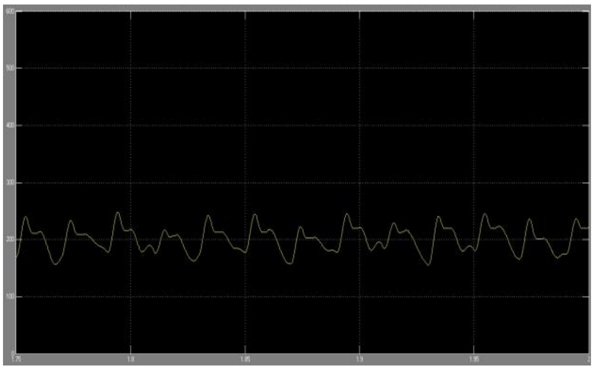

Fig. 8. Output voltage of Rectifier

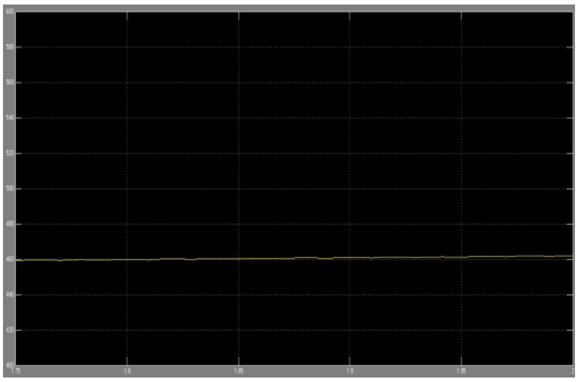

Fig. 9. Output voltage of Boost converter

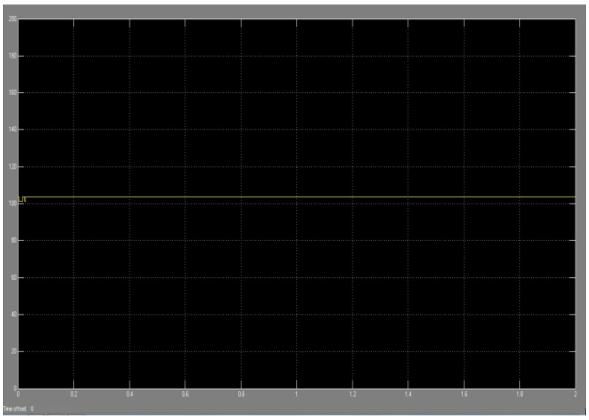

Fig. 10. Output of battery charging circuit

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A. Performance Metrics

The amount of distortion in the voltage or current waveform is quantified by means of an index called the total harmonic distortion (THD).

THD in the current is defined as,

$$\%THD_i = 100\frac{I_{dis}}{I_{s1}} \qquad (19)$$

Where,

I_{dis} distortion current

I_{s1} sinusoidal input current

Fig. 11. shows that FFT analysis of WTGS using PMSG. From the fig it is clear that THD of the system by using ordinary 180^o mode operation of inverter is 59.53%.

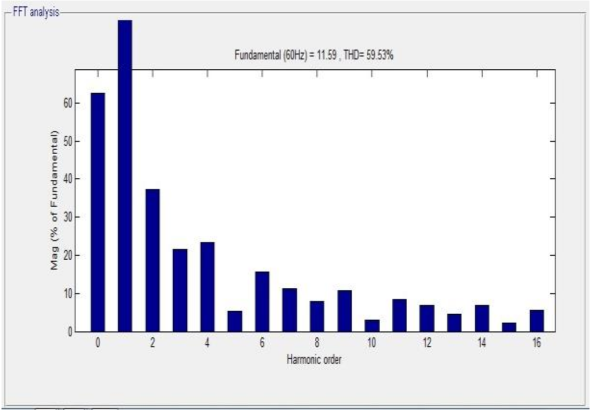

Fig. 11. THD of WTGS without PWM

Fig. 12. shows that FFT analysis of WTGS using PMSG. From the fig it is clear that THD of the system by using PWM inverter is 42.74%.

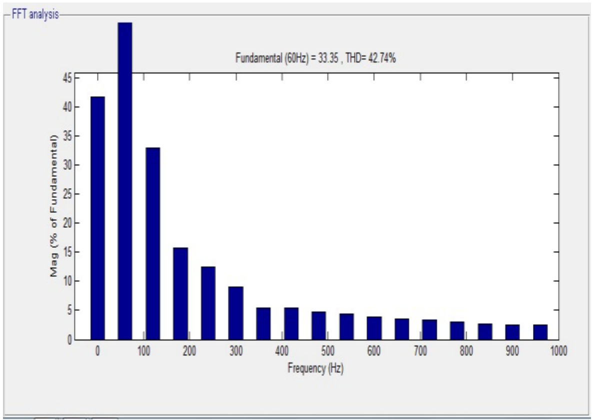

Fig. 12. THD of WTGS using PWM inverter

VII.CONCLUSION

A control strategy for a direct – drive stand – alone variable speed wind turbine with a permanent magnet synchronous generator was simulated using MATLAB/Simulation. The controller is capable of maximizing output of the variable – speed wind turbine under fluctuating wind. Simulation of WTGS using PMSG has been done with and without PWM inverter and output voltage analyzed. THD level with PWM inverter is much less than without PWM inverter. The main disadvantage of this method is that difference between the % THD in both cases are that much high. Further study is needed to reduce the THD level to a large extended. A battery charging application has also been designed.

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