Simulation and Performance Analysis of Thirteen Level Multilevel Inverter Tied to a Grid connected Wind Energy System

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***Abstract*— this paper presents an overview of multilevel inverter for the power quality improvement of wind energy system. It produces waveform with less harmonic content and work on the principle of pulse width modulation. Generation of pulses by this method gives ripple less waveform and less harmonic content closely to pure sinusoidal waveform. As the depreciation of conventional energy sources, non-conventional energy sources are now being used for the electrical power generation and in non-conventional energy sources most popular method is wind energy generation system. But there is some difficulty of integration of variable output voltage wind energy generation system to power system grid operating at constant voltage & frequency. We have developed a simulink model of a multi-level inverter connected in cascade using MATLAB and applied the developed model in the field of electric power generation from wind. By using the DC voltages constant or variable at different level we can achieve AC voltage at desired level with the help of multi-level inverter connected in cascade and by this method we can achieve any level of voltage at output.**

Keywords—Multilevel inverter; Non-conventional Energy; Wind Energy; Pulse width Modulation (PWM)

1. Introduction

Now a days non-conventional energy sources becomes very important aspect for energy generation because conventional energy sources are diminishing day by day and among the non conventional energy sources, wind energy keeps much importance because of ease and clean with many technical advantages over other non conventional sources. The fast technological progress in wind energy generation system (WEGS) has results into large number of new scopes in all over the world. As in all over the world the use of renewable source for generation of electrical is growing very fast [1-6]. So, there is an urgent need that technology available in the present research field of WEGS should be moved to field.

In 1891, the first wind driven electric generator was developed by Dane Poul LaCour. During World Wars 1 and 2 Danish engineers made some advancement in the wind generator and used the advanced machinery to fulfill the requirement of energy. All modern wind turbines used now are based on the wind turbine developed by the Danish company F. L. Smidth. So this turbine which was built in 1941–42 may be thought as base of recent turbines. This was the first turbines in which modern airfoils were used first time, based on the advanced knowledge of aerodynamics.

In industries, electric drives of vast range are used spreading from low power drives to very large power up to MW level. And it has become very complex matter to supply electric drives of different range from one converter. So this problem was solved by introducing multilevel power inverter configuration which is able to deliver energy at high voltage and power to medium level and lower level. And with the application of multilevel inverter it becomes possible to integrate renewable energy sources to grid for a high power application [6]. So non-conventional energy sources may also be used to attain high power ratings.

Concept of multilevel inverters was first introduced in 1975 where 3 levels were achieved in 1st multilevel inverters. After that technological development has taken place in the field of multilevel converters. The high power sources are obtained by combination of number of power semiconductor switches and many low voltages rating DC source. In these converters the generated staircases are converted to high level voltage thus high power rating gained. In inverter constant DC voltage is converted to AC power in the form of sinusoidal or some derived form of sinusoidal [7]. An inverter can be compared with multilevel converter as both do the same function the difference lies in terms of power level only. An inverter is employed in low power range up to few KW but working power range of multilevel converter is in MW.

2. Multilevel Inverter

There are 3 topologies used in multilevel inverters as

2.1 Cascaded H-Bridges

As shown in figure 1 the two DC sources which may be current or voltage source are connected to separate H-bridge inverter. Each H-bridge inverter consists of four switches. By operation with different combination of switches we can achieve at least 3 different voltage levels AC output.

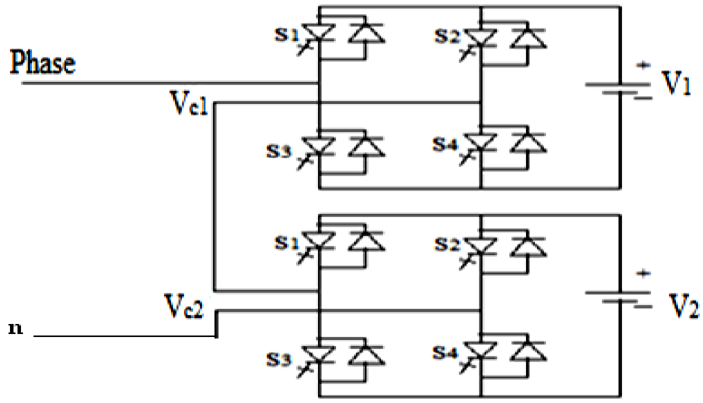


Figure 1. Three level Cascaded inverter

2.2 Multilevel Inverter Diode-Clamped type

This inverter found its suitability for integration of high DC source to high voltage grid lines also for controlling the speed of motors. But this inverter requires skilled operation and continuous monitoring to avoid discharging and over charging [5].

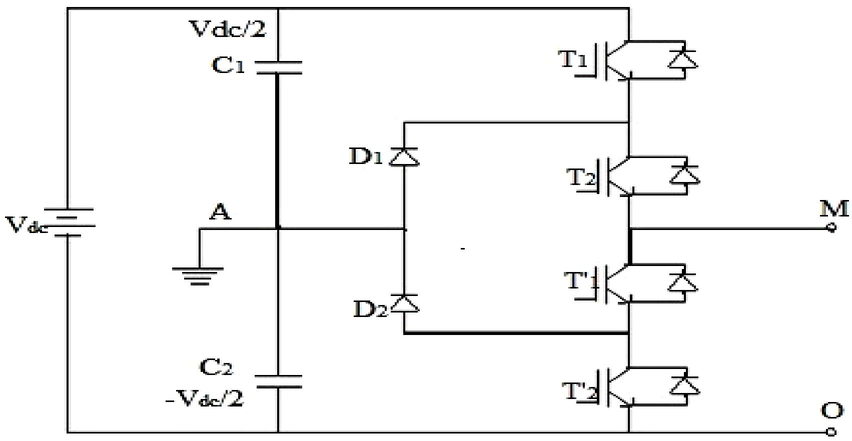


Figure 2. Three level diode-clamped multilevel inverter

The DC current source is divided in 3 parts as shown in fig 2. For the purpose we have used two capacitors namely C1 and C2 connected in series, these are high rating capacitors. The common point of two capacitors 'A' will be at same voltage level so considered as reference of ground. Depending on conduction combination of various switches we get 3 values of output voltage V_{AM} which are described as follows: When switches T_1 and T_2 are turned on voltage V_{AM} becomes equal to voltage $V_c/2$, whereas when switches $T_1^{'}$ and $T_2^{'}$ are turned on the voltage V_{AM} becomes equal to the voltage level $-V_{dc}/2$ while V_{AM} is equal to 0 voltage when switches S2 and S_1' are in conduction mode [5].

Difference between our proposed inverter and straight two level inverter is because of diodes D_1 and $D_1^{'}$ which we have used in our circuit. The switch voltage is maintained at half value to that at DC bus voltage by the two clamping diode used here. During the conduction of switch T_1 and T_2 voltage across A and O is V_{dc} so we have $V_{MO} = V_{dc}$. The clamping diode D'_1 maintain the equal voltage sharing between the non conducting switches and voltage of capacitor C1 is blocked by $T_1^{'}$ and that of C_2 is by $T_2^{'}$. Actually the voltage across V_{AM} is the output AC voltage and V_{AO} is the input DC voltage. The difference of two voltages V_{AM} and V_{MO} is available across C_2 as $V_{dc}/2$. So we can say the proposed converter is actually acting as a DC-DC converter, converting output voltage at 3 different level: V_{dc}, $V_{dc}/2$, and 0 which is obtained by removing the output between A and O.

2.3. Multilevel Inverter Capacitor Clamped type

In terms of design this type of inverter matches with a diode clamped type inverter. But dissimilar from diode clamped inverter in terms of capacitors that we are using here at the places of diodes for clamping purpose. In this inverter only combination of two switches are used to gain output voltage at different level. It's very complex to chase output voltages at all of them, so we have charge each capacitors before putting the converter in operation [5] [7].

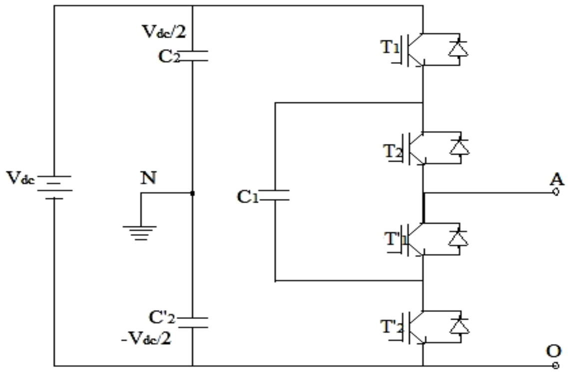


Figure 3. Capacitor clamped 3-level inverter

As shown in Figure 3 this is basic circuit configuration of a phase lagging type capacitor-clamped inverter. The main advantage of this designs its ability to regulate the output by self, for the purpose this configuration has flying capacitors. So with the help of this device voltage can be clamped to a voltage level equal to that of a single capacitor.

A three-level output voltage can be obtained across A and N by the inverter shown in Figure 3, as follows $V_{an}= V_{dc}/2$, 0, or $–V_{dc}/2$. By turning on the switches T_1 and T_2 it is possible to attain voltage level $V_{dc}/2$ whereas $–V_{dc}/2$ level is obtained at output by switching on T_1' and T_2' voltage and 0 level can be achieved by switching on the switches either (T_1,T_1') or (T_2,T_2') simultaneously. The capacitor C_1 is charged by switching on the switches T_1 and T_1' to discharge T_2 and T_2' switches have to be switched on. The charge on capacitor $C_{1\ can}$ be balanced by switch combinations of 0-level.

3. Multi-Level Inverters

Multilevel electrical converter technology has arisen recently as a really vital various within the space of dynamic medium-voltage energy management. In recent years, trade has begun to demand higher power equipment that currently reaches the power unit level. Controlled ac drives within the power unit vary are sometimes connected to the medium-voltage network. Now a day, it's onerous to attach one power semiconductor switch on to medium voltage grids (2.3, 3.3, 4.16, or 6.9 kV). For these reasons, a brand new family of structure inverters has developed because the resolution for operating with higher voltage levels [8-16].

Multilevel inverters contain associate array of power semiconductors and electrical device voltage sources, the output of that generate voltages with stepped waveforms. The commutation of the switches permits the addition of the electrical device voltages that approach high voltage at the output, whereas the facility semiconductors should stand up to solely reduced voltages.

3.1. Construction Features of Inverter

The devices that are accustomed convert DC-to-AC voltages are called inverters. The aim of associate electrical converter is to vary a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. The frequency of output voltage can be mounted or variable at a hard and fast or variable frequency. Once the input DC voltage is variable and therefore the gain of electrical converter is constant then the obtained output voltage is additionally variable in step with input [5] [16].

On the opposite hand, if the dc input voltage isn't variable and it's mounted, then by variable the gain of the electrical converter a variable output voltage is obtained, that is often accomplished by pulse-width-modulation (PWM) management at intervals the electrical converter [6]. The gain of electrical converter could also be outlined because the magnitude relation of the ac output voltage to dc input voltage.

Figure 4 shows a single-phase bridge electrical converter. it's four switches. Once switches S_1 and S_4 ar turned on at the same time, the input voltage V_s seems across the load. If switches S_2 and S_3 are turned on at the same time, the voltage across the load is reversed and is $–V_s$

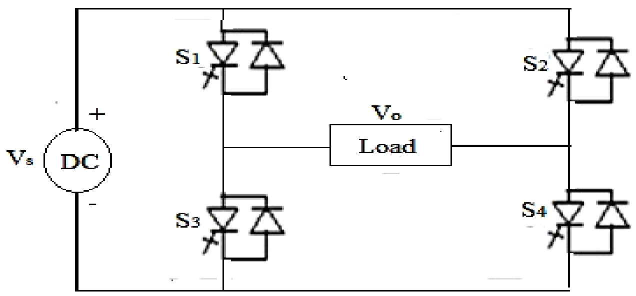


Figure 4. Single-phase inverter

The waveform for the output voltage is shown in Figure 5.

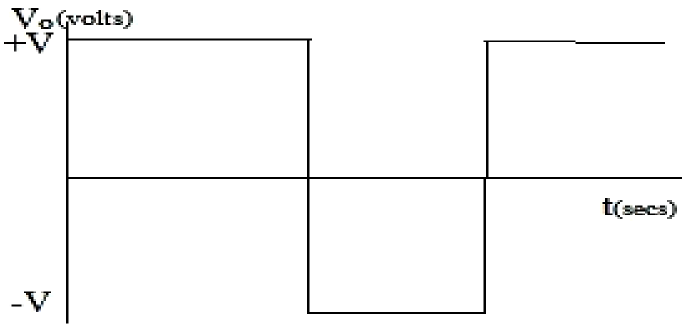


Figure 5. Output voltage waveform

The rms output voltage can be found-

$$V_o = \sqrt{\left(\frac{2}{T}\int_0^{T/2} Vs^2\, dt\right)} = V_s \quad (1)$$

And, the instantaneous output voltage in a Fourier series as-

$$vo = \sum_{n=1,3,5.....}^{\infty} \frac{4Vs}{n\pi} sin\ \ nwt \quad (2)$$

And, n = 1, the equation gives the rms value of fundamental component as-

$$V_1 = \frac{4V_s}{\sqrt{2}\ \pi} = 0.90V_s \quad (3)$$

The instantaneous load current i_0 for an RL load becomes-

$$i_o = \sum_{n=1,3,5....}^{n} \frac{4Vs}{n\pi\sqrt{\sqrt{R^2+(nwL)^2}}} \quad (4)$$

Where,

$$\theta_n = (\tan^{-1}\frac{nwL}{R}) \quad (5)$$

When diodes in switches S_1 and S_4 conduct, the energy is fed back to the dc supply and that then square measure known as feedback diodes. And, three-phase inverters square measure usually used for high-voltage applications. Three-phase inverters, like single-phase inverters, take their dc offer from A battery or additional typically from a rectifier. A basic three-phase electrical converter could be a six-step bridge electrical converter. It uses a minimum of six switches.

In electrical converter nomenclature, a step is outlined as modification within the firing from one switch to consecutive switch in correct sequence. For a six step electrical converter every step would be of 60° interval for one cycle of 360°. This suggests that thyristor would be gated at regular intervals of 60° in correct order in order that a 3-phase ac voltage is created at the output terminals of a six-step electrical converter. 3 single-phase [*fr1] (or full)-bridge inverters will be connected in parallel as shown in Figure 6.

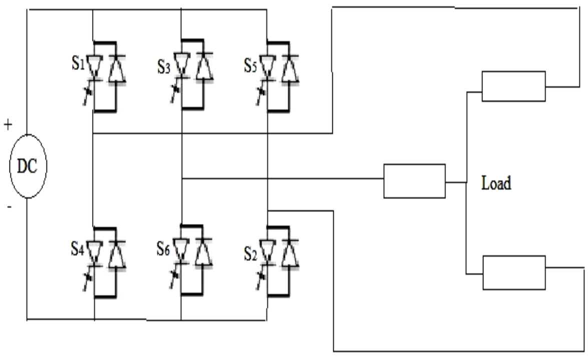


Figure 6. Three-phase bridge inverter using thyristors as a switch

For getting three-phase balanced (fundamental) voltages the gating signals of single-phase inverters ought to be advanced or delayed by 120° with relevance one another. If the output voltages of single-phase inverters don't seem to be absolutely balanced in magnitudes and phases output voltages are going to be unbalanced. Three-phase inverters area unit used for variable-frequency drive solicitations and for top power solicitations like HVDC power transmission [11].

A basic 3-phase electrical converter has 3 single-phase electrical converter switches every connected to 1 of the three load terminals. For the foremost basic management theme, the operation of the 3 switches is coordinated so one switch operates at every sixty degree purpose of the fundamental output undulation.

3.2. Wind Energy Conversion System

WECS generate electricity by using the power of wind to drive an electrical generator. The conversion of the kinetic energy of the incoming wind air into the electrical energy takes place in two steps: the extraction device, i.e., the wind turbine rotor captures the wind power movement by means of aerodynamically designed blades, and converts it into rotating mechanical energy, which drives the generator rotor.

The electrical generator then converts this rotating mechanical power into electrical power. A gear box can be used to match the rotational speed of the wind turbine rotor with one that is suitable for the generator. The electrical power is then transmitted to the grid through a transformer [13]. The connection of the wind turbine to the grid is possible at different levels of voltage, with a common level being 600-700 V. Power electronics converters can also be used for improved power extraction and variable speed operation of the wind turbine. Figure 7. Presents the topology of a complete wind energy conversion system (WECS).

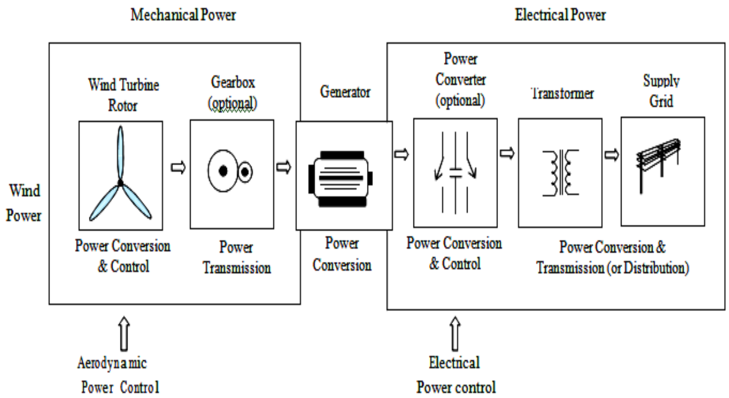


Figure 7. A generic Wind Energy Conversion System

The electrical losses embody the losses thanks to the generation of power, and {also the} losses occur severally of the facility production of wind turbines and also the energy used for lights and heating. The losses thanks to the facility generation of the wind turbines square measure principally losses within the cables and also the electrical device. The low-tension cable ought to be short thus on avoiding high losses. For contemporary turbine system, every rotary engine has its own electrical device to boost voltage from the voltage level of the wind turbines (400 or 690 V) to the medium voltage [17].

3.4. Speed Control of WECS

Speed control of WECS is used to control the speed of wind at any wind speed. Following are various types of speed control of WECS at fixed-speed and variable speed so that the aerodynamic rotor can be matched accordingly.

3.4.1. Fixed-Speed WECS (The Type 1 WECS)

Fixed-speed WECS are electrically simple devices, containing of an aerodynamic rotor driving an Induction (Squirrel cage or wound rotor) generator which is directly connected through gearbox and shaft. The slip, and hence the rotor speed of generator, changes with the amount of power generated. These rotor speed fluctuations are, however, very small (approximately 1 to 2 percent). Therefore, this WECS is generally referred to as a constant or fixed speed system. The rotor speed is calculated by the frequency of the supply grid, the gear ratio and the number of pole-pairs of a generator, regardless of the wind speed. These are designed to attain maximum efficiency at one particular wind speed. At wind speeds above and below the rated wind speed, the energy capture does not achieve the maximum value. Fixed-speed WECS are mechanically simple, reliable, stable, robust and well-proven. They have cheap maintenance and electrical parts. Conversely, these suffer from the drawbacks of mechanical stress, limited power quality control, and poor wind energy conversion efficiency[16][17].

3.4.2. Variable Speed WECS

As the size of WECS is becoming larger and the dissemination of wind power in power system is increasing, the inherent problems of fixed-speed WECS become more and more definite, particularly in areas with relatively weak supply grid. To overcome these problems and to fulfill with the grid-code connection requirements, the trend in modern WECS technology is to implement variable-speed concepts. With the advancements in power electronics converters, which are used to connect wind turbines to the grid, variable speed wind energy systems are becoming corporate. Variable-speed WECS have some advantages of increased power capture, improved system efficiency, improved power quality with less flicker, reduced mechanical stress, reduced fatigue, and reduced acoustic noise. Furthermore, the presence of power converters in wind turbines also delivers high potential control capabilities for both large modern wind turbines and wind farms to accomplish the high technical demands executed by the grid operators[12][17].

The main features of variable-speed WECS are manageable active and reactive power (frequency and voltage control), offer quick transient and dynamic response under all power system conditions, effect on network stability and improved power quality. Their disadvantages include losses in power electronic elements and increased cost. Variable-speed WECS are designed to attain maximum aerodynamic efficiency over a wide range of wind speeds. It is possible to continuously adjust (increase or decrease) the rotational speed of WECS according to the wind speed. As the wind turbine works at flexible rotational speed, the electrical frequency of the generator changes and must therefore be decoupled from the grid side frequency. This is attained by using a power electronic converter system, between induction or synchronous generator and the grid [17][18].

The network electrical frequency decouples from the rotor mechanical frequency by the power converter to enable variable speed operation of the wind turbine. Variable-speed operation can be attained by using any appropriate combination of generator (synchronous or asynchronous) and power electronics interface, as it will be explained in the following subsections.

There are three commonly used configurations of variable-speed converters. They have the variable-speed with partial-scale frequency converter, the variable-speed with full-scale frequency converter and with limited speed. These configurations can use any of the power-control mechanisms, namely stall, pitch or active stall control. As mentioned earlier, the pitch control mechanism is the most widely used.

3.4.3. Limited variable-speed (the Type 2 WECS)

In this concept there is use of a wound rotor induction generator (WRIG), which is directly connected to the grid. A capacitor bank is used for reactive power reimbursement and a soft- starter is employed for smoother grid connection. A unique feature of this concept is that it has a adjustable rotor resistance, which can be varied to control the slip. By this way power output in the system is controlled, typical speed range being 0-10% above synchronous speed. Following figure 8 shows the block diagram of Wound rotor induction generator.

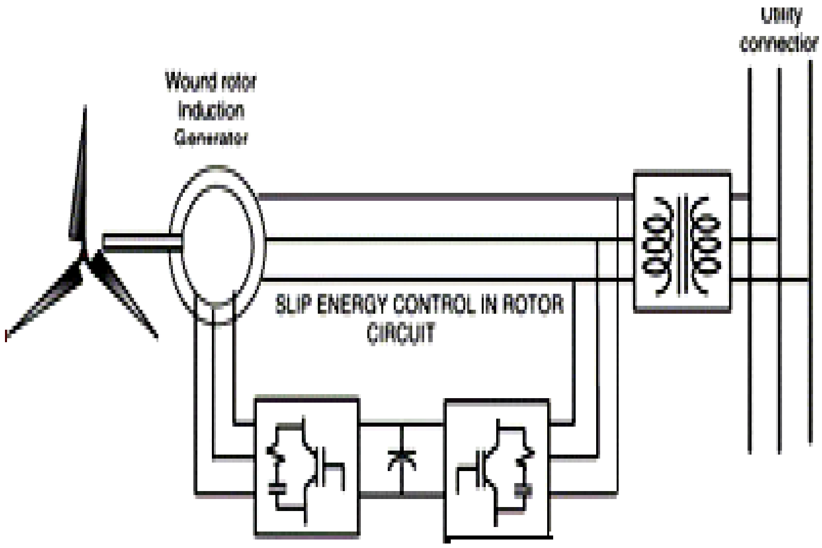


Figure 8. Wound Rotor Induction Generator

3.4.4 Variable-Speed with Partial Scale Frequency Converter (the DFIG or Type 3 WECS)

This configuration is also called Doubly-Fed Induction Generator (DFIG) which corresponds to the limited variable speed WECS with WRIG and a partial scale frequency converter (generally rated at approximately 30% of nominal generator power) on the rotor circuit.

For taking current into or out of the rotor winding it uses a WRIG with slip rings and variable speed operation is obtained by injecting a controllable voltage into the rotor at slip frequency. The rotor winding is fed through an adaptable frequency power converter, normally founded on two AC/DC IGBT based voltage source converters (VSCs) connected by a DC bus . A DFIG system supplies power to the grid through the stator while the rotor insert power into system if the rotational speed of the generator is more than critical value otherwise absorb. If the generator runs above synchronous speed, power will be supplied from the rotor through the converter to the network, and the rotor will absorb power from the network through the converters if the generator works below synchronous speed.

The partial-scale frequency converter reimburses for reactive power and provides a smoother grid connection. It has a comparatively wide range of dynamic speed control, typically 30% around the synchronous speed. Its main disadvantages are the use of slip rings and high short-circuit currents in the case of grid faults (as compared to the Type 4 WG – presented in the next subsection). Thus in this system, there is possibility to control both active and reactive power, providing high grid performance. In addition, the power electronics converter allows the wind turbine to act as a more dynamic power source to the grid. Following figure 9 shows us the block diagram of doubly fed induction generator.

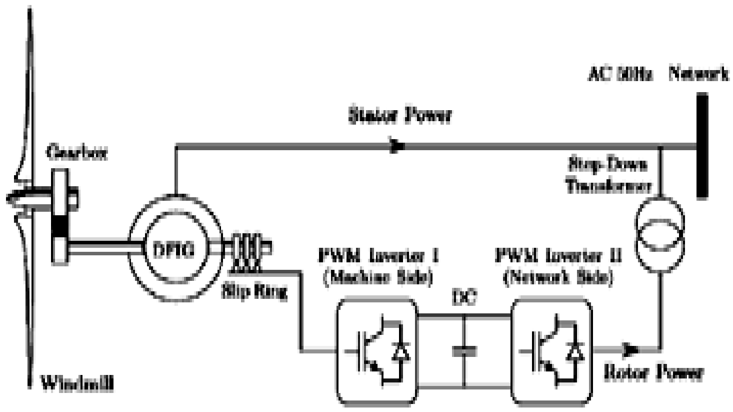


Figure 9. Doubly Fed induction generator

3.4.5. Variable-Speed with Full-Scale Frequency Converter (the Type 4 WECS)

This configuration relates to the complete variable speed turbine, with the generator connected to the grid via a all-out frequency device. The frequency converter utilizes for reactive power compensation and provides a smoother grid connection. The generator is disconnected from the grid by a DC link. The power converter permits the system to control active and reactive power very fast. Now the generator can be electrically excited (WRIG or WRSG) or by a permanent magnet (PMSG). The gearbox may not be required in some configurations using a direct driven multipole generator. Enercon, Made and Lager way are well- known manufacturers of this topology. The synchronous generators and full-scale converters configuration is also referred to as Type 4 generators. This also links to the power of squirrel cage induction generator [9]. Figure 10 shows the block diagram of squirrel cage.

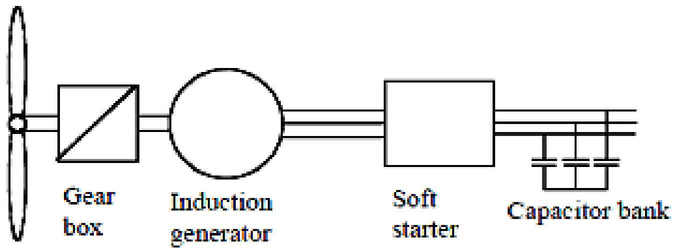


Figure 10. Squirrel Cage Induction Generator

While DFIGs have gained popularity in recent years, Type 4 generators have been gradually capturing the market. As compared to the DFIGs, Type 4 WECSs have a wider range for the controlled speed, are more efficient, less complicated, and easier to construct from an electrical engineering perspective. In addition, the Type 4 WECS can be made direct- driven system without using a gear box, resulting in reduced noise, installation and maintenance costs. SG can also be connected to diode rectifier or VSC. A major cost benefit is in using a diode bridge rectifier. The synchronous generators can be electrically excited or excited by permanent magnets. The Permanent Magnet Synchronous Generators (PMSG) do not need any external excitation current, meaning less losses, improved efficiency and more compact size[10]. Following figure 11 shows us the block diagram of Wind energy conversion system with PMSG [16][17][18].

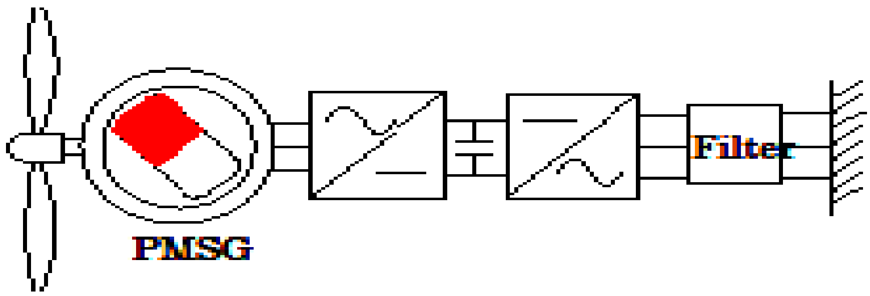


Figure 11. Wind Energy Conversion System with PMSG

4. Simulation and Results

4.1 Single-Phase Thirteen Level Inverter

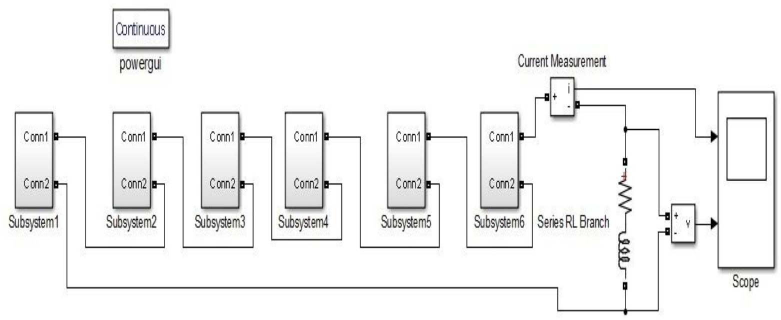
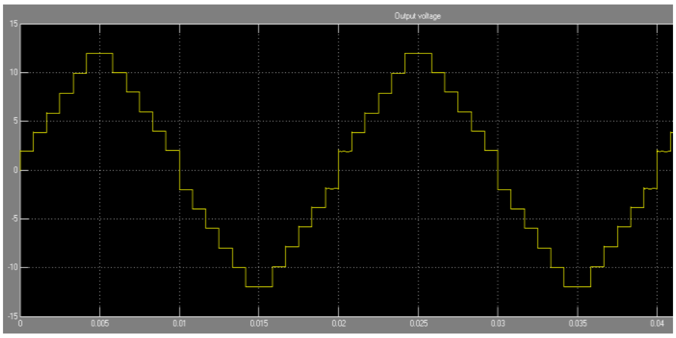


Figure 12. Single-phase 13-level multilevel inverter (Simulation circuit)

Here as shown in figure in figure 12 we have connected six H-bridge converter in cascade to obtain 13 level multi-level inverter. The load for analysis purpose we have taken is of RL type. Voltages applied across load we are measuring by voltmeter and waveforms are obtained and can be seen in scope.



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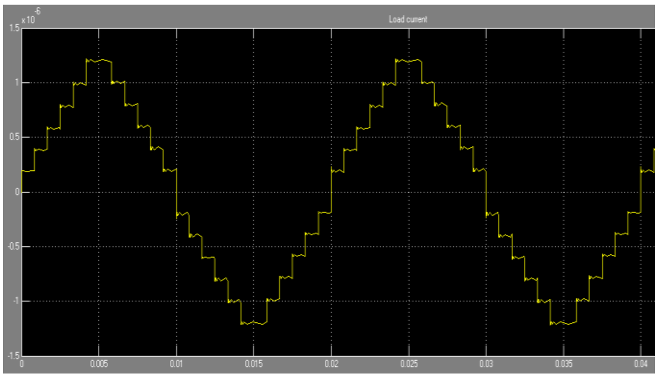

(b)

Figure 13. Simulated Output 1-phase waveforms of 13-level cascaded inverter with separate DC sources (a) voltage (b) current (when load is RL

4.2. Three-Phase Cascaded Thirteen Level Inverter

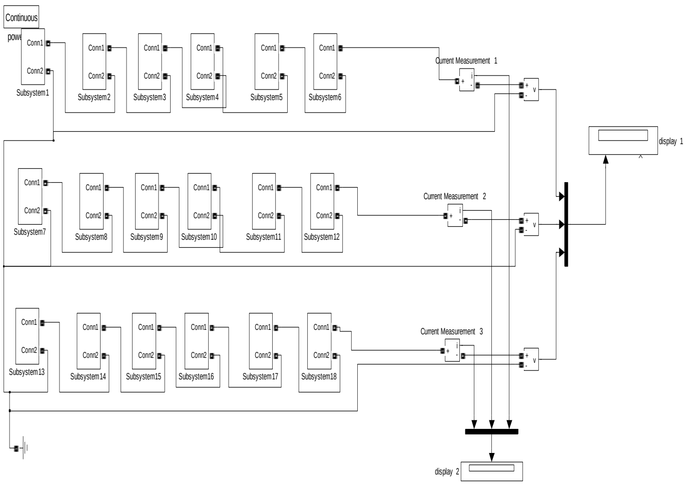

Figure 14. Single-phase 13-level multilevel inverter (Simulation circuit)

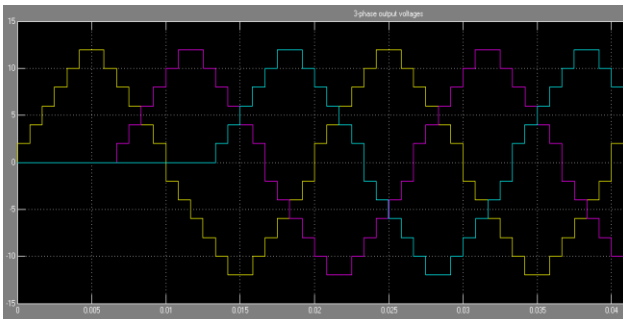

Figure 15. Simulated 3-phase Output voltage waveforms of 13-level cascaded inverter with separate DC sources.

In Figure 15, forward the positive sequence three-phase system, output voltage of section B lags output voltage of section A by a hundred and twenty electrical degree. The road voltage, V_{AB}, therefore, leads voltage of section A by thirty electrical degree, that is consistent with the three-phase theory.

The major benefit of three phase system lie in the fact that magnitude of all odd harmonics multiple of three get eliminated or reduced in the line voltage by third cycle section shift feature. Therefore, only other odd harmonic voltage has to be filter out from pre filtered output voltage. For example in three phase system only we have to design filter only for third order harmonics and 5^{th}, 7^{th} and 11^{th} harmonic are eliminated by themselves [5].

So from comparison of harmonics contents 9^{th} is the lowest harmonics in single phase converter output voltage while 13^{th} is the lowest harmonics in 3-ϕ system.

4.3. Simulated Model For Interfacing With WECS

Grid Interface of WECS with PMSG, 13 Level NPC Multilevel Inverter

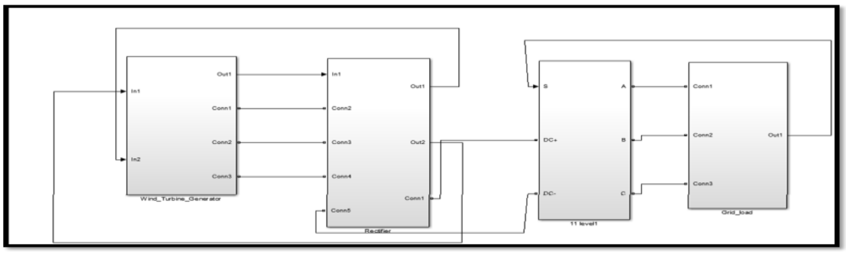

Figure 16. Experimental Model for Grid Interface of WECS with PMSG

4.4. Simulated Model for Wind Turbine Generator

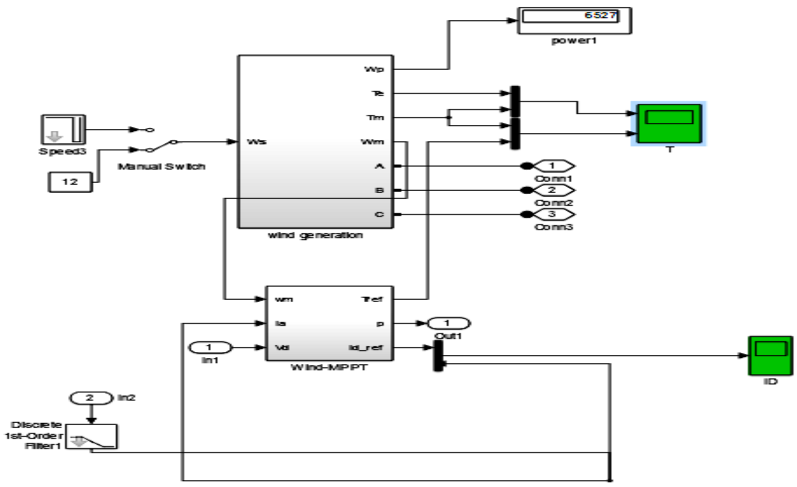

Figure 17. Model of Wind Turbine Generator

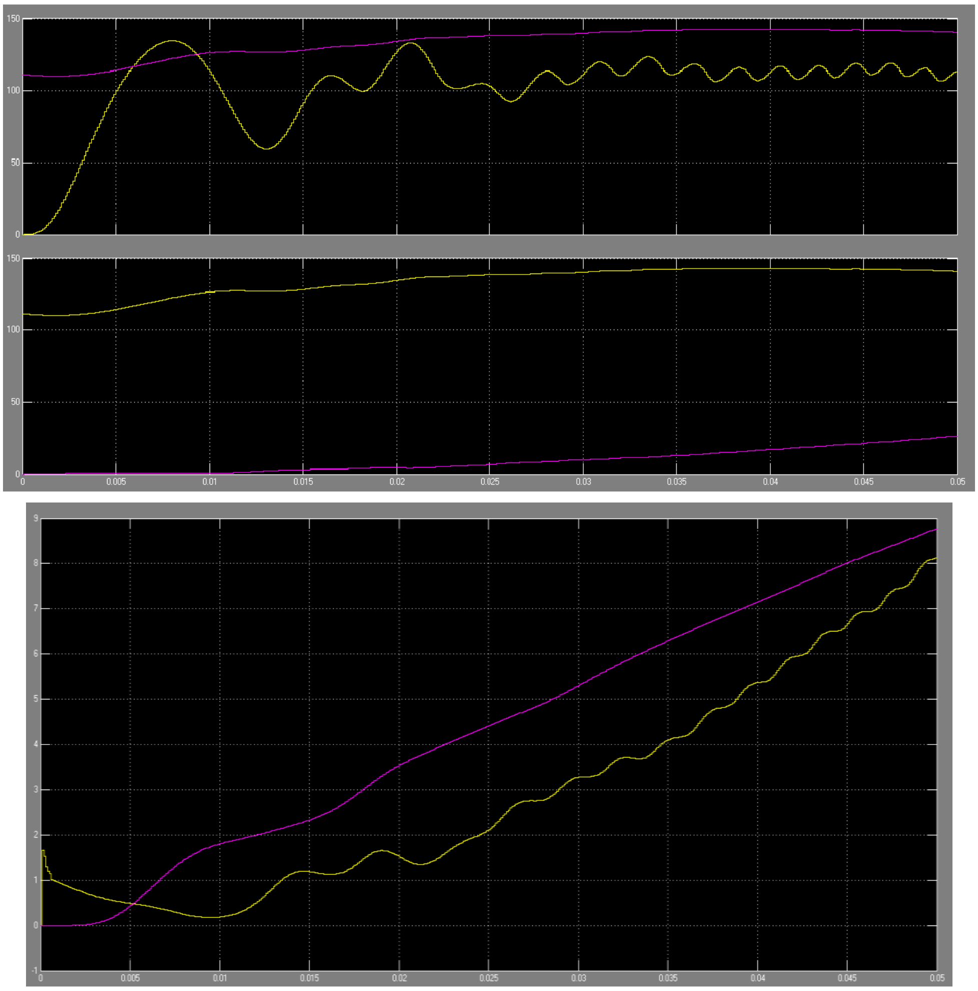

Figure 18. Results for Simulated Model for wind turbine

5. Simulated Model for Grid Load

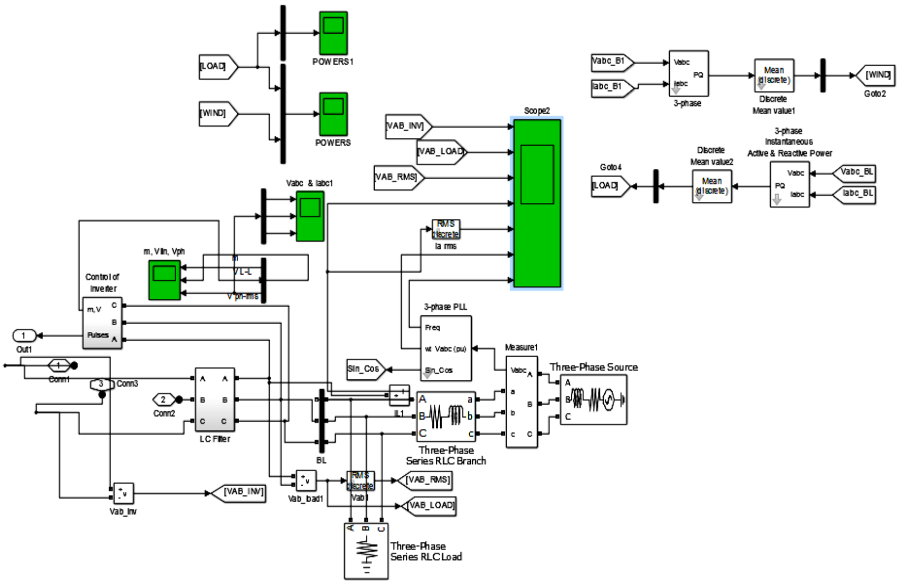

Figure 19. Experimental Model for Grid Load

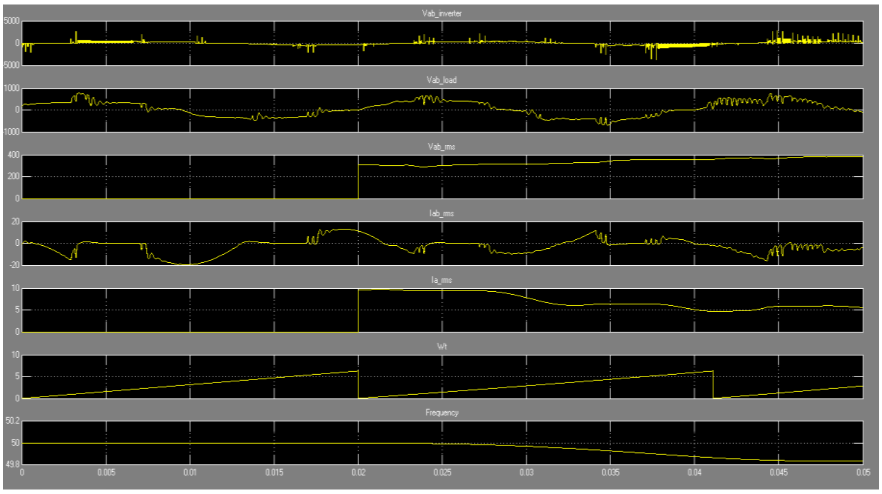

Figure 20. Results for Grid Load

6. **Future Scope**

A multi-level electrical converter will Control each active and reactive power at the same time and severally, charge batteries by engrossing active power from the grid, rated higher due to structure topology and effective in power oscillation damping therefore it will be used with FACTS devices for enhancing the voltage and angle profile.

The reliableness of the turbine operating at variable speed will be improved considerably employing a permanent magnet synchronous generator (PMSG) coupled directly to turbine & therefore the wind turbine is free to operate at any speed this result in less stress on shaft and there is no requirement of gearbox system to regulate the turbine speed it will any be jury-rigged by mistreatment HVDC links.

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