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A Review on Various Topologies of Generators, Power Converters and Control Schemes in Wind Energy Systems

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ABSTRACT

In the field of renewable energy, conversion of wind energy has become a point of major interest to the researcher. Converters are no more a small part of the wind energy system (WES) due to the development of generators in the WES and advancement in applications of power electronics in the WES. This paper presents a review of different topologies of converts used in the extraction of energy from wind using various generators and their combination with different converter topologies. Control scheme/complexity, cost, the power consumed, and efficiency are the points considered for the comparison of converters–generator combination schemes.

KEYWORDS: *Power electronics, wind energy system (WES), converters, wind energy, wind generators, synchronous generators (SG), induction generators (IG), maximum power point tracking (MPPT), permanent magnet synchronous generators (PMSG), doubly fed induction generators (DFIG), pitch control*

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ABBREVIATIONS

WES Wind Energy System

WT Wind Turbine

SG Synchronous Generators

IG Induction Generators

MPPT Maximum Power Point Tracking

PMSG Permanent Magnet Synchronous Generators

DFIG Doubly Fed Induction Generators

SRIG Slip Ring Induction Generator

VAWT Vertical-Axis Wind Turbine

HAWT Horizontal-Axis Wind Turbine

PWM Pulse Width Modulation

VVVF Variable Voltage Variable Frequency

IGBT Insulated Gate Bipolar Transistor

GTO Gate Turn Off Transistor

AC Alternating Current, A

DC Direct Current, A

MC Matrix Converter

TSR, λ Tip to Speed Ratio

ρ Density of Air

V_w Wind Speed, rpm

P_{wind} Wind Power, kW

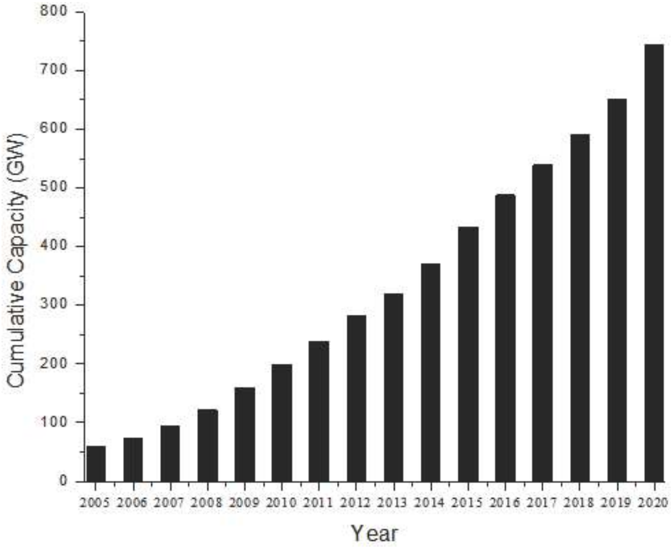
$P_{turbine}$ Turbine Power, kW

ω_r Angular Turbine Rotation Speed, rad/sec

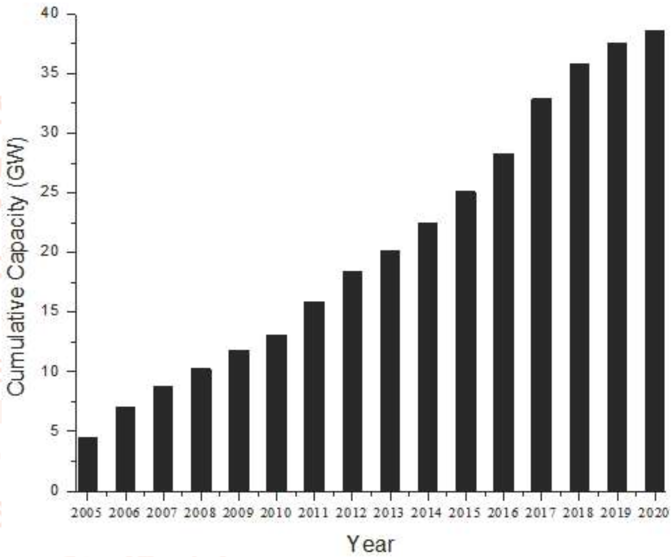
INTRODUCTION

It is a well known fact that we have limited amount of fossil energy resources like oil, gas, coal. Worldwide consumption of fossil resources is increasing day by day. Now to fulfill the increasing power demand renewable energy resources are used. Renewable energy is also known as green energy or clean form of energy due to the absence of emission or any other by-products which are unwanted and that can unbalance earth's environment. After the energy crisis in 1973 due to high cost of these oil and fuel gases, western countries moved their focus towards exploring solutions to effectively utilize renewable energy recourses [1]. So the mission is to create a clean and an inexhaustible energy sources from wind, tidal, biomass, solar and geothermal energy becomes more convenient [2-4]. From all these available energy resources, to generate clean energy to fulfill the increasing energy demand the most efficient clean energy resource is wind energy [5].

In recent years, researchers had published different schemes of converters to interact with power grid. These power converters enhance the power extraction and also allow variable-speed operation of turbines used in WES. To extract maximum power, constant voltage and frequency a control scheme is needed to be designed for variable speed operations. There are several such schemes are listed in literatures and all schemes having power electronic application are designed in such a way that the output power at all possible wind speed can be maximized. The speed of wind ranges between rated to the cut-in speed, both limits are totally depended on what type and size of generator is used in WES. Fig. 1(a) shows the total global installed capacity from 1996 of WES to 2018 and Fig. 1(b) shows the India wind power installed capacity 2005 to 2019 [7]. Total of approx. 743 GW generation capacity of WES was installed till 2020 worldwide, only in year 2020 the generation capacity of WES is increased by 93 GW and expected to attain approximately 1412 GW till the end of year 2025. India is on fourth place in the list of countries with a total installed generating capacity of 38.6 GW in the world's green energy generation [6].



(a) Global wind power installed capacity 2005 to 2020 [6].



(b) India wind power installed capacity 2005 to 2020 [7].

Fig.1. World and India wind energy trend [6-7].

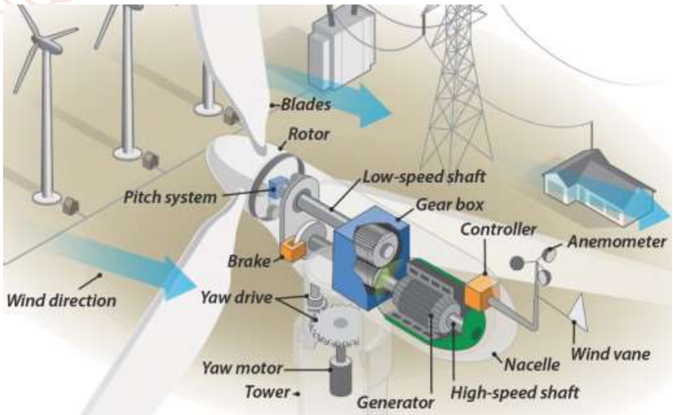


Fig.2. Parts of wind turbine [8].

This paper provides difference between the available power converter topologies of wind energy system and also discuses on the different converter-generator combinations available for wind energy conversion.

Background of Wind Energy System

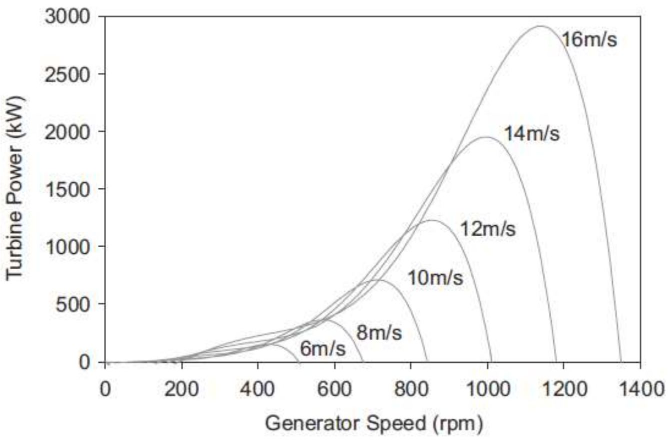


Fig.3. Output power characteristics of wind turbine [13].

WES is a clean, renewable and green energy source which is used for the production of electrical energy without any involvement of fossil fuel sources and problems due to them [9]. Energy obtained from wind can be used directly or indirectly as mechanical or electrical power in different systems respectively. In WES kinetic energy of wind is converted into electrical energy in two stage conversion using generators connected with wind turbine (WT). WT are the most crucial part of WES. These WTs can be installed either on vertical or on horizontal axis forming vertical-axis wind turbine (VAWT) or horizontal-axis wind turbine (HAWT) respectively. HAWT type is very commonly used in WES as it has several merits as compare to VAWT like, it has simple configuration especially for higher rates besides their high efficiency and low cost [10]. The amount of power captured using any WT is fixed and depends on the turbine size, shape, type and is given by,

$$P_{wind} = \frac{\rho \pi R^2 v_w^3}{2} \quad ...(1)$$

$$P_{Turbine} = \frac{\rho A v_w^3 c_p}{2} \quad ...(2)$$

Where, turbine power is $P_{Turbine}$, ρ (density of air), A (swept turbine area give by $A=\pi R^2$), wind speed is represented by V_w and c_P (performance coefficient). The value of c_P for any WT is defined by ratio of tip to speed (λ) with turbine radius R and angular turbine rotation speed ω_r is given by,

$$TSR \; or \; \lambda = \frac{\omega_r R}{v_w} \quad ...(3)$$

The relationship of c_P and λ can be observed by suing MATLAB programming for different values of pitch angle. It is evident that the maximum efficiency from turbine can be achieved at one specific TSR [11-12]. The value of TSR is required to be kept at optimal operating point to achieve maximum output power at all possible wind speed. Turbine rotational speed versus turbine output power can be plotted as it is shown in Fig. 3. It is clear from the curves that with the rise and fall in wind speed, the maximum power point also increases and decreases [13].

A. Horizontal-Axis WT

In HAWTs system, generators are generally kept at tower top as it is shown in Fig. 4(a). Due to slower rotational speed of turbine blades a gearbox is used, so that a suitable speed can be obtained to drive the generator. Tall tower based installation provides HAWTs configuration an incomparable advantage over other configuration of producing maximum amount of energy. It is listed in the literatures that as for every 10 meter increase in towers height, power generated also increases by 34% due to 20% increase in wind speed [14]. HAWTs have an advantage of having variable blade pitch, as it gives ability to the blades to adjust its angle to achieve maximum output possible. And one more advantage is higher efficiency than other configuration, but it also has some drawbacks. First, construction cost of the tower is higher as it has to hold all the major parts of the system. Second, additional control is required for turbine blades direction control. And third due to reflection from the high towers of HAWT system it causes problems in the radar installation [15].

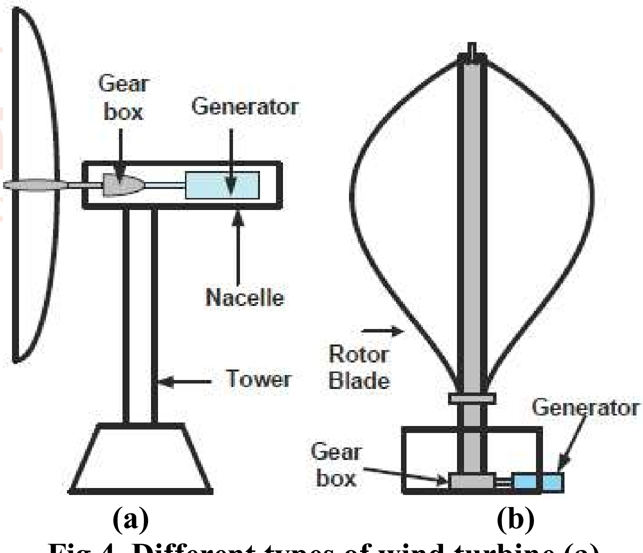


Fig.4. Different types of wind turbine (a) HAWT, (b) VAWT [16].

B. Vertical-Axis WT

In VAWTs system, blades are arranged vertically w.r.t. ground and rotated around a shaft. Advantage of VAWTs system is relation between wind and the blades, in this system blades are always in perpendicular to the wind. Hence, there is no requirement of additional controller as HAWTs system [14, 15] and also have easier maintenance process as illustrated in Table 1. As it is shown in Fig. 4(b) generator and gearbox are fixed on the ground. VAWTs system can be installed in different locations like roof tops and highways. One of the problems with VAWTs system is that it cannot achieve higher speeds due to shorter tower. Hence, the obtained power from VAWT system is less compared to that of HAWT systems [17].

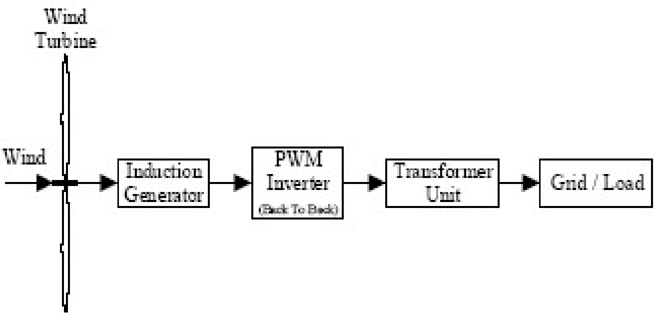
TABLE 1 Features Compression of Horizontal and Vertical Axis Wind Turbine [15-17]

Feature	Horizontal Axis Wind Turbines	Vertical Axis Wind Turbines
Efficiency	Low	High
Tower Height	Small (around 10 m)	Large (around 100 m)
Blades Rotation Speed	Low (3-7 m/sec)	High (5-12 m/sec)
Rotational Blades Area	Small	Large
Maintenance	Simple	Complex
Noise Effect	0-10 dB	5-60 dB
Generator location	Ground	Tower Top
Wind Dependency	Independent	Dependant
value (at 12 m/sec)	0.05	0.08
Application	On Shore	Both On and Off Shore

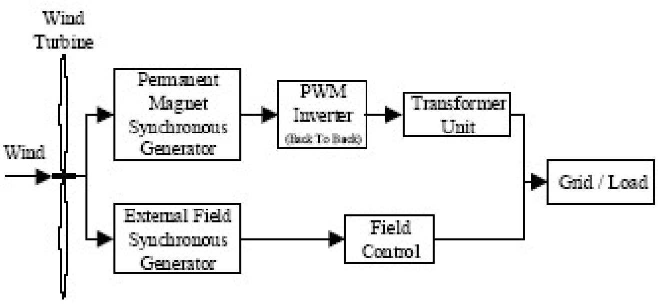
Parts and Control of Wind Energy System

A. Electric Generator

Many wind energy system are established and listed in literature for different power ratings. This leads to different generators application in WES like synchronous generators (SG), induction generator (IG) and doubly fed induction generator (DFIG). Generally, synchronous generators are utilized. However, nowadays instead of synchronous generators induction generators are in use due to its lower cost, self fault protection, rugged construction and its ability to electrical power at various speeds. This property enables induction generators operation in isolated, which can be used to provide power supply to the remote regions [18-20].



(a)



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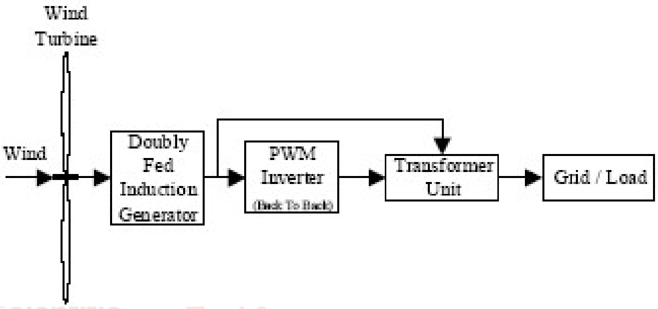


(c)

Fig.5. Block diagram for different wind energy conversion schemes (a) Induction generators, (b) Synchronous generators and (c) Doubly fed induction generator.

After recent advancement in power converters, application of induction machine in wind energy conversion is becoming more acceptable. IGs are in use for quite a while with settled speed WTs. IGs are robust, inexpensive and there maintenance requirement is also low. But to supply the reactive power it requires a capacitor bank and this is one of the fundamental disadvantages. For variable speeds application pulse width modulation (PWM) inverters (back-to-back) are used. Here the generator side inverter provides torque control, by keeping the frequency in permissible limits. Whereas, inverters connected on the grid side gives better control over reactive power. To control the voltage during variable speed WT is in use the reactive power can be attained from reactive compensator as shown in Fig. 5 [21].

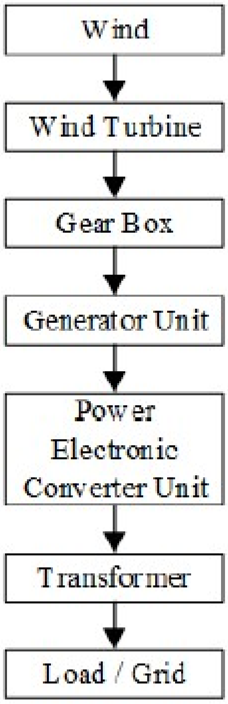


Fig.6. Block diagram of general flow of wind energy system

DFIGs are used on a wide scale in energy conversion for green energy as wind turbines. And it is broadly utilization of slip ring induction generator (SRIG). The stator in this is connected to framework using slip rings to be supplied by a converter [22]. This offers an operation at ± 33 % of the synchronous speed. And power is decide by value of slip, which the converter of the DFIG must be intended for [23]. The rated power should be around 30% of the generator ratings for this ± 30% variation in the speed. In SRIG reactive power source is required whereas reactive power compensation in DFIG is done by DC capacitors and grid side converters [24].

Due to the advantage of variable producing reactive power the industry solely utilizes substantial SGs. A PWM converter (back to back) is used in between grid and SG. Power to the grid is now controlled by the PWM inverter connected to the grid side [25] and the generated side PWM inverter is regulating the electromagnetic torque. In the future, designing of generator will be focused on the weight and cost optimization with fault ride through capability. Instead of depending on the conventional as well as commonly used generators now researchers are moving towards designing of new generators with smaller size, light weight, near zero resistivity and higher efficiency [26].

B. Power Electronics Converter Topologies

Power electronics converters are one of the key parts used in WES. Here in these systems AC to AC conversion is needed hence voltage regulators or frequency regulators are required as shown in Fig. 7.

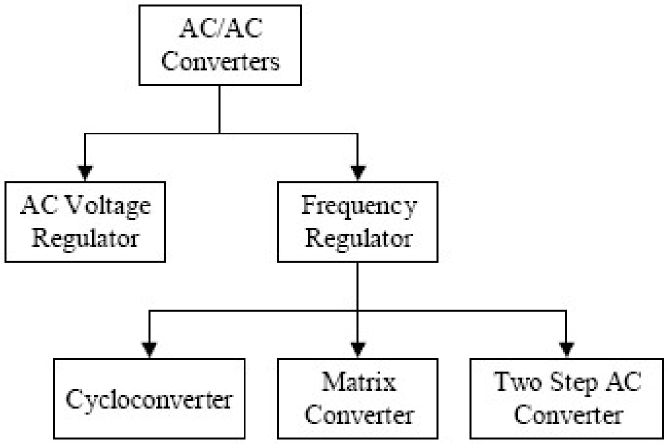
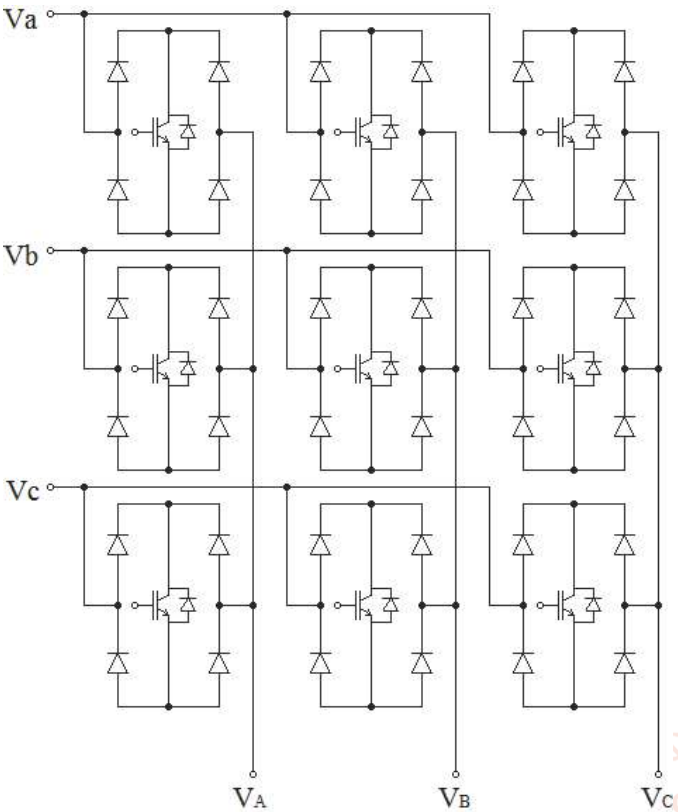


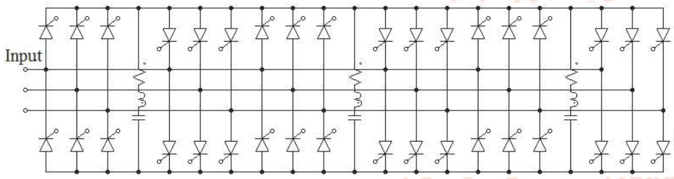
Fig.7. AC-AC Converters types for WES.

1. **AC Voltage Regulator**: It controls r.m.s. voltage at the load without changing the frequency. This voltage control can be obtained by either of two strategies: ON/OFF control or phase control. In ON/OFF control scheme phenomena of forced commutation is used in power electronic switches i.e. power transistors, MOS-controlled thyristor, IGBTs and GTOs. While in phase control scheme natural commutation of semiconductor devices (i.e. thyristor or triac) is used. But in WES for variable speed operation application of AC voltage regulators is not possible as it is difficult to control output frequency [27].
2. **Frequency Converter**: It converts any AC voltage at fixed frequency in the desirable frequency. For this the conversion process is categorized into two types: first one is directly (without using DC link or single step method) or indirectly (two step method, here DC link is used between two ends).

2.1. Cycloconverter: The cycloconverter now a days with the development in power semiconductor switches are developed down to earth for different application of variable voltage variable frequency (VVVF) drives like, low speed high power in steel and cement industry. And, it is also utilized in aircraft application for variable frequency operations. The essential use of cycloconverter is to provide a lower frequency AC voltage from an AC voltage of higher frequency. Conventionally commutated cycloconverter have following primary constraints: (i) at low yield voltage it has poor input displacement power factor; and (ii) restricted extends of frequency for efficient operation [28].



(a)



(b)

Fig. 8. Shows (a) Three phase matrix converter topology and (b) Three phase cycloconverter topology with isolated loads.

Table 2 Comparison of Different Type of Pitch Angle Control [12]

Parameter	Hybrid Control	Soft Computing Control	Robust Control
Performance	High	Moderate High	Moderate High
Convergence Speed	Faster	Faster	High
Performance (at Variable Speed)	Very High	High	High
Cost	Moderate	Moderate	High
Complexity	Moderate	Low	High
Reliability	High	High	Moderate High

2.2. Matrix Converter (MC): This direct converter is consisting of IGBT switches (nine switches) as shown in Fig. 7(b) with a simple construction as there is no DC link needed. This converter can also control the phase angle between applied voltage and applied current as its inherent ability. It is also possible to obtain an unity input displacement factor with matrix converter [29]. But, still matrix converters are not able to establish its position industry. This is due to its disadvantages: (i) its ratio of voltage transfer from input side to output for sinusoidal waveform is limited to 0.866, (ii) Due to less number switches in matrix converter that allow the bidirectional flow of current, some of its topologies required large number of switching devices as compared to conventional rectifier inverter combination topology, (iii) due to high frequency harmonics it needs an external filter to reduce them and (iv) the requirement of clamping circuit in matrix converters for switches over voltage protection, as it operates for inductive loads.

2.3. Two Step AC Converter: This converter is an example of indirect or two step method of conversion for frequency converters. It is also a method to decouple the two frequencies. As demonstrated in Fig. 9 this two step AC converter circuit is sub-divided into two parts one is rectifier and other one is an inverter. Initially in rectifier part of this converter forced-commutation of three phase rectifies is needed to achieve a desirably converter voltage at the output terminals of rectifier. Now the responsibility of driving the motor wheel and controlling speed for different load torque is on inverter part of this converter [28-30].

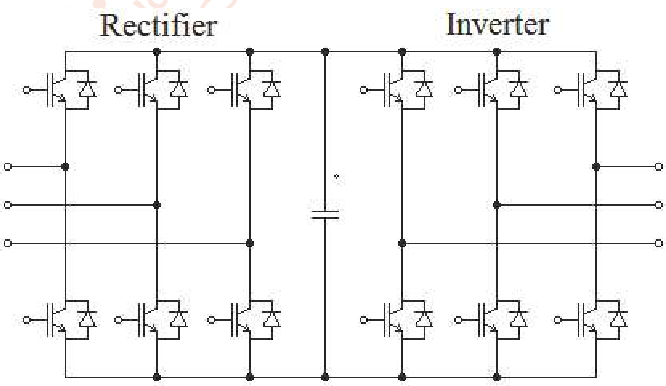


Fig.9. Shows Two Step AC Converter

C. Control Schemes for WES

In WES the effective generation of power can only be obtained by using overall control schemes. These control schemes are based on different subsystems of any wind energy systems; on the bases of this control schemes for WES are divided into three types. The first one is pitch angle control also known as aerodynamic control; second is maximum power tracking control (MPPT) or active power control by using different algorithms; and third one is machine/grid side control as shown in Fig. 10 [31].

1. **Pitch Angle Control:** This control scheme works by changing turbine blade angle; this is done to control aerodynamic power and speed of the turbine. When there is any sudden large change in wind flow this control scheme ensures WT's mechanical safety. As shown in Fig. 10 and Table 2 there are different pitch angle control schemes available in practical and literatures.

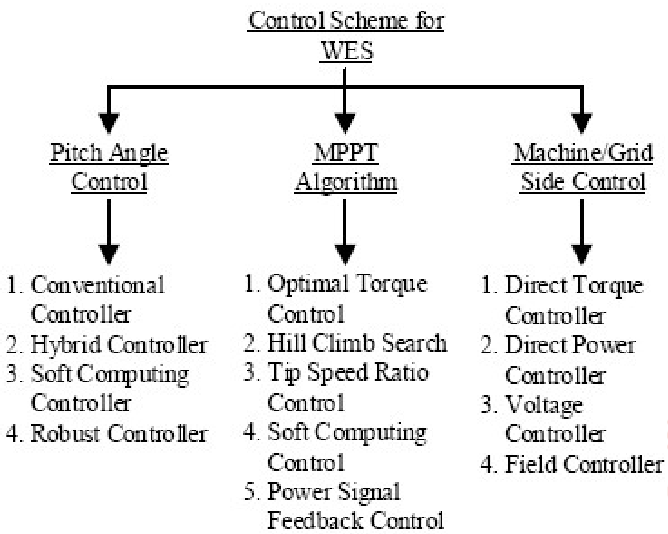


Fig.10. Different Control Schemes in WES

2. **MPPT Control:** In any WES the most desirable features is its operation at maximum power point under all circumstances. So, MPPT control enables WES to optimize its efficiency by extracting maximum energy possible from a wide wind speed range using different algorithm. There are different control schemes are listed in literatures for maximum power extraction at any instance. Table 3 lists the comparison of these different algorithms. In future MPPT based research should be concentrated on the combinations of two or more methods, like application of fuzzy logic using perturb and observe algorithm and optimal torque control scheme can also be used with perturb and observe algorithm to solve the inherent problem, this will give optimized results.

3. **Machine and Grid Side Control:** This control scheme is used for variable speed operation of WES, this control scheme can obtain maximum energy from variable wind speed. Under this scheme the rotor speed is changed by using different controllers to achieve stability and maximum power of the system. The power quality, synchronization with the grid and grid code compliance can be improved by using grid side control and also provides effective active power control. This grid side control can be done using grid side controllers; these controllers so not play any role in energy conversion. Grid side controllers are only responsible for the power quality and synchronization with grid.

Table 3 Comparison of Different Type of Maximum Power Point Tracking Control Algorithms

Parameter	Perturb and Observe Control	Optimal Torque Control	Power Signal Feedback Control	Tip Speed Ratio Control
Prior Knowledge	No	Yes	Yes	No
Convergence Speed	Depends	Fast	Fast	Fast
Wind Speed Measurement	No	No	Yes	Yes
Memory Requirement	No	No	Yes	No
Performance(at Variable Speed)	Good	Very Good	Good	Very Good
Complexity	Simple	Simple	Simple	Simple

Conclusion

As the WES has become center of attraction for the researcher and highly researched area. A comparative and concise on different converter topologies, generators and control schemes has been achieved through this paper. The different wind turbines along with the basic wind energy system background are discussed. Indian and worldwide wind energy production details are displayed. It also presented the various technical aspects related to WES, including types of electrical generator, topologies of power electronics converter and different control schemes. This paper also recommends the use of matrix converter in WES due to its advantageous features like, its wide output frequency range and besides it's simple and compact form its ability of controlling input displacement factor. All control schemes discussed are attempting to achieve maximum power from the WTs at any instance. The continuous efforts are made in research for WES so that converter and control techniques can be more efficient and cost effective, and the researcher are also focusing on reduction of WT's weight and size in a hopes of achieving an economically viable green energy extraction method as a solution to increasing environmental issues.

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