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Electrical Power Extraction Control Strategies in Wind Energy Conversion System

Shubhrata Jha[1], Samina Elyas Mubeen[1], Arbind Kumar Mishra[2]

[1]M. Tech Scholar, [2]HOD Electrical & Electronics Department, REC Bhopal(M.P.)

Abstract - at present interest in *wind* ***energy has been outpacing other*** *renewable methods* ***for new electrical power generation. Most wind turbine simulators are quite limited in their ability to model unsteady aerodynamic effects induced by the turbine; thus, still researches are going on to improve the performance of wind energy conversion system (WECS).The fixed-speed wind turbines possess the merits that they are simple, robust, and require lower construction and maintenance cost. However, their operation speed is fixed and cannot be controlled with the variation of the wind speed, which results in lower energy conversion efficiency. An advantage of the variable speed wind turbine is that the rotor speed can be adjusted in proportion to the wind speed in low to moderate wind speeds so that the system can extract maximum possible power. The optimum realization of a wind energy conversion system depends on the best possible control strategies that not only regulating the output voltage and frequency of electrical signal shall also extract energy from the wind at utmost efficiency. This paper presents a comparative assessment of various academic works till date on wind turbine control. The pitch angle control and maximum power point tracking of a wind turbine is mainly focused.***

Keywords: wind energy, MPPT, PMSG,WECS .

I. INTRODUCTION

Energy issues pose one of the greatest challenges facing society. More than 86% of the world's energy currently comes from (unsustainable) fossil fuels, and worldwide energy demand continues to grow rapidly [1]. In the last decade, wind power as an energy source has increased its share in energy production, especially in central parts of Europe and on the west coast of the U.S. Globally, wind derived power is the fastest growing energy source. India has the fifth largest installed wind power capacity in the world. Now wind is more economically feasible than solar or biomass for electricity generation, with some projections predicting wind, given good environmental conditions and proper government subsidies, to be of similar cost to fossil fuels for electricity generation [2]. Despite this promise, significant improvements in the deployment and control of wind turbines are needed if wind is to contribute a significant portion of electricity worldwide [3].

The biggest challenges related with wind power is the unpredictable character of the wind. After having the excellent arrangement of wind turbine and its components at steady reasonably high speed wind, there are variations in speed and direction of the wind which affect the ability of the wind turbine to deliver power. Larger wind turbine systems have complex control systems which automatically track changes in wind direction and speed, and adjust turbine orientation, blade pitch, and generator gearing to maintain the desired electrical output. Small turbine systems are typically much less sophisticated and can be used for the improved performance. The main purposes of a controller in a wind energy system are:

- Prevent damage to the wind turbine
- Prevent damage to the load
- Maximize power production

Optimum power extraction is popular control strategy as it helps to achieve optimum wind energy utilization. Though the large scale wind energy conversion system uses both the turbine control and generator control to regulate the extracted power. Small scale systems usually do not have turbine side control popularly known as pitch angle control. It usage only the generator side control to regulate the extracted power. Several mechanisms are used to stop turbine rotation including rotation of the turbine out of the wind, either vertically (tilt) or horizontally (yaw), frictional breaks, electrical breaking and blade pitch adjustments to cause the blades to stall, i.e. furl. Most small machines use a mechanical system to rotate the turbine out of the wind and may use electrical breaking, while larger machines furl the blades and have frictional breaks as well.

II. WIND TURBINE MODEL

A wind turbine is a device that converts the kinetic energy of the wind into mechanical energy. This mechanical energy can be used for specific tasks (such as grinding grain or pumping water) or for driving a generator that converts the mechanical energy into electricity that is supplied to the power grid or individual users. Modern wind turbines fall into 2 basic groups:

a. Vertical Axis Wind Turbine (VAWT)

b. Horizontal Axis Wind Turbine (HAWT)

Fig.1 depicts a basic layout of a wind turbine converting wind power into shaft power to drive an electrical generator or other load. The relation between the wind speed (vw) and aerodynamic available wind power (Pw) can be expressed by the equation, $P_w = \frac{1}{2}\rho\pi R^2 \times v_w^3$.Where ρ is the air density and R is the radius of the turbine blade. Fig. 2 shows the power produced from a typical small wind turbine as a function of wind speed. Below the "cut in speed" there is not enough wind power to overcome friction, thus no power is produced. Above the cut-in speed the power increases rapidly to the "rated speed". Generally the turbine produces its rated power at the rated wind speed, though some manufacturers quote numbers differently.

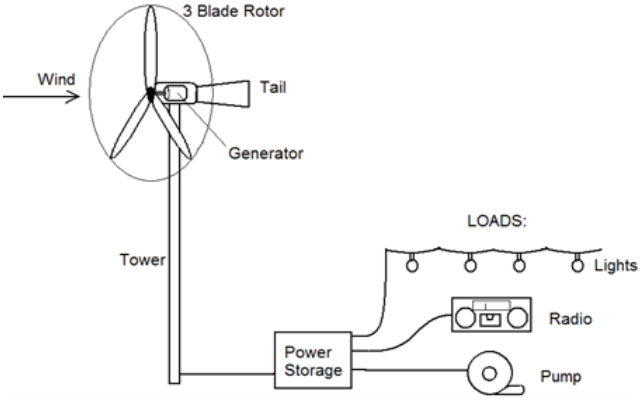


Fig. 2.1 A typical small wind turbine power system.

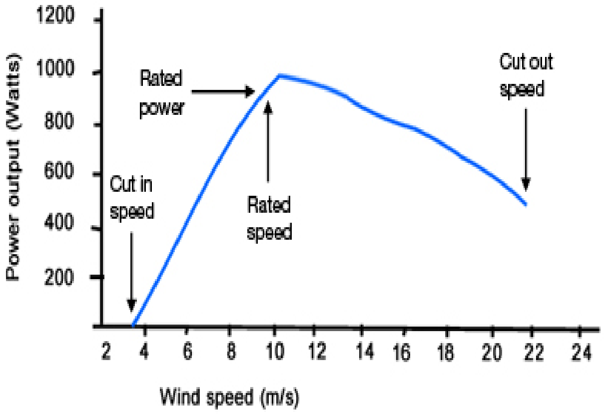


Fig.2 WECS power output vs wind speed

The extracted mechanical power from the turbine is only a fraction of the available power. The extracted mechanical power (Pm) from the wind turbine is given by $P_m = C_p(\beta, \lambda)P_w$. The power coefficient CPdefining the aerodynamic efficiency of the wind turbine rotor is the function of blade pitch angle (β) and tip speed ratio (λ). It depends on such factors as the number of blades, and the pitch and shape of the blades. The maximum value CP can attain is theoretically around 57%, however the highest performing turbines generally only attain values in the 40% range while values in the 30% range are more common .The coefficient of performance is a strong, fig.3 nonlinear function of the "Tip Speed Ratio.

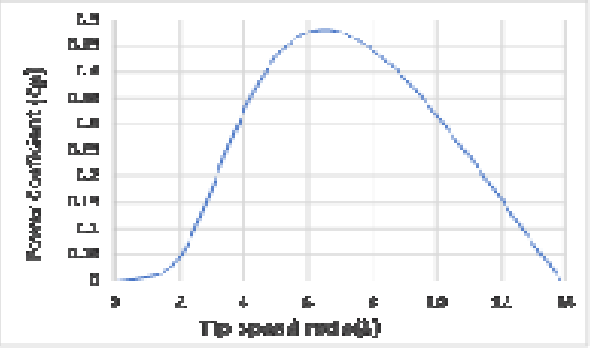


Fig.3 A typical power coefficient vs tip speed ratio curve

The tip-speed ratio, λ, or TSR for wind turbine is the ratio between the tangential speed of the tip of a blade and the actual velocity of the wind v. The tip-speed ratio is related to efficiency, with the optimum varying with blade design. Higher tip speeds result in higher noise levels and require stronger blades due to large centrifugal forces.

$$\lambda = \frac{Tip\ \ Speed\ of\ blade}{Wind\ speed}$$

The tip speed of the blade can be calculated as ω times R, where $\omega$is the rotor rotational speed in radians/second, and R is the rotor radius in meters. Therefore, we can also write:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{wR}}{\boldsymbol{v}}$$

Where ω is the rotor speed of the turbine which is also the speed of the generator rotor without gear.The tip-speed-ratio is the linear speed of the outer extremity of the turbine blade divided by the wind speed.For small generators usually there is no provision for pitch angle control.

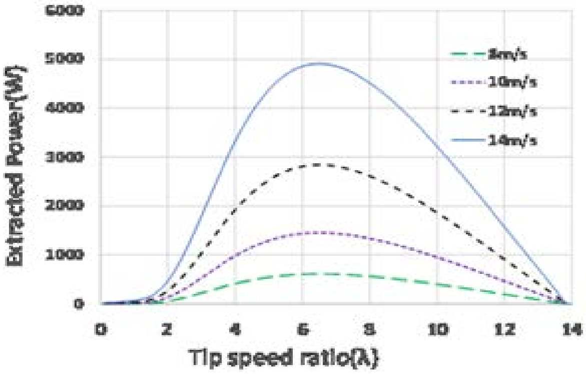


Fig.4 Extracted power (Pm) vs tip speed ratio (λ) at varying wind speed

III. PREVIOUS WORK

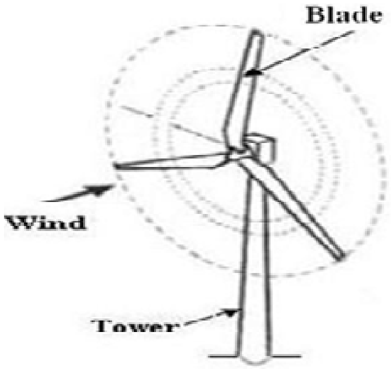
The wind turbine can extract maximum power Pm when the turbine operates at maximum power coefficient (CP).For a typical wind turbine the extracted power vs tip speed ratio curve is shown in Fig.4It is seen that the aerodynamic efficiency of a wind turbine is maximum for a particular value of tip speed ratio. Hence for maximum possible power extraction at available wind speed, it is necessary to keep the rotor speed at an optimum value of the tip speed ratio (λ). If the wind speed varies, the rotor speed should be adjusted to follow the change.

IV. WIND ENERGY CONVERSION CONTROL PROPOSED METHODOLOGY

(a). Pitch angle control.

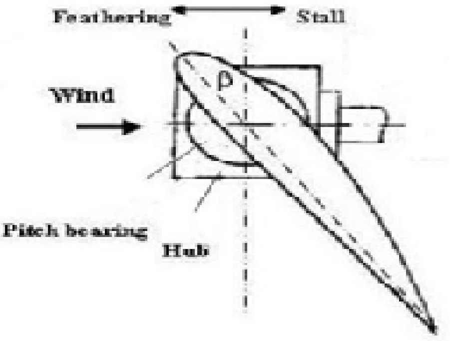
Wind turbine pitch control system can change incidence of rotor blades in a wind power generation system based on real-time wind speed for the purpose of adjusting output power, achieving higher utilization efficiency of wind power and providing protection for rotor blades. The pitch angle is the angle at which the blade surface contacts the wind. It is often variable to ensure optimum operation of the turbine in varying wind conditions and to prevent electrical overload and over speed in high winds. Gears in the hub of the rotor allow the pitch to be varied. When wind speed is not higher than the rated speed, the blade incidence stay near the angle 0° (highest power point), which is similar to that of a generator with constant pitch, generating an output power that changes along with wind speed. When wind speed is higher than the rated speed, the pitch control mechanism changes blade incidence so that the output power of generator is within the allowed range.

Typically a wind turbine pitch control system is built with a controller, pitch control mechanisms, a backup power supply, and a feedback module monitoring generator output power. High performance MCUs or DSCs are often selected as the controllers of pitch control systems. They are responsible for giving instructions to pitch control mechanisms based on real-time wind speed, preset power rating, pitch information, and output power signal of generator. Pitch control mechanisms are commonly made up of rotary encoders, gate drivers, IGBT modules and servo motors. Each motor blade needs a single control mechanism, which means three mechanisms in total are required. After the instructions given by controller are received, the gate drivers, IGBT modules of these mechanisms drive their associated motors to change blade incidence. Meanwhile, the real-time pitch information is sent back to controller by rotary encoders. Feedback module is composed of voltage sensor and current sensor which the collect voltage and current signals from generator and send to controller. In order to feather the blades in the event of an emergency situation, backup power is needed. Backup power can be implemented with batteries, ultra-capacitors, or even a hybrid solution offering the best of both options.



Pitch control is one of the most ubiquitously used control techniques to regulate the output power of wind turbine generators. This method relies on variations in the power captured by the turbine as a function of the hydraulically actuated blade pitch angles. The pitch control system is easy to implement; however, the response is slow and the output power variation is large. The aerodynamic power control for the variable speed wind turbine can limit the power injected into the turbine by reducing the angle of the blades. Fast torque changes caused by wind gusts impact generator performance.

Most small wind turbines have 2 or 3 fixed blades rotating about a horizontal axis directly driving a permanent magnet generator. The control system generally consists of a mechanical system for furling the turbine in high winds, and with perhaps a power controller and electrical breaking system.



(b). Power maximization control:

Nowadays, most of the wind turbines applied in industry are variable-speed wind turbines. Among various types of variable speed WECSs, most widely applied in industry are:

- Doubly-fed induction generator (DFIG) WECSs with reduced-capacity power converters,

- Geared/gearless squirrel-cage induction generator (SCIG) WECSs with full-capacity power converters
- Geared/gearless wound-rotor synchronous generator (WRSG)
- Permanent magnet synchronous generator (PMSG) WECSs with full-capacity power converters

In the DFIG WECSs, only 30% of the rated power is processed by the power converters, which greatly reduces the cost of the converters while preserving the capability to control the speed of the generator in the range of about of its rated speed [6]. In SCIG,WRSG and PMSG WECSs, full-capacity power converters are needed to process the power generated by the generators up to the rated power of the systems. With the application of the full-capacity power converters, the generators are fully decoupled from the grid, and are able to operate in the full speed range. As the large scale wind turbines(up to 10 MW) attract more and more attention nowadays, the direct-drive PMSG based WECSs which are very suitable for large scale wind plants

The direct-drive wind turbine PMSGs do not have the gearbox between the wind turbine and the PMSG rotor shaft, which avoids the mechanical power losses caused by the gearbox. Moreover, the removal of the gearbox also helps in reducing the cost of the system. The wind turbine PMSG transforms the mechanical power from the wind into the electrical power, while the rectifier converts the AC power into DC power and controls the speed of the PMSG. The controllable inverter helps in converting the DC power to variable frequency and magnitude AC power. With the voltage oriented control algorithm, the inverter also possesses the ability to control the active and reactive powers injected into the grid.

The wind power mainly depends on geographic and weather conditions and varies from time-to-time. Hence it is necessary to construct a system that can generate maximum power for all operating conditions. In these scenario, recently, permanent magnet synchronous generator (PMSG) is used for wind power generating system because of its advantages such as; better reliability, lower maintenance and better efficiency.

The scheme with a proper control algorithm to modify duty-cycle of DC-DC converter for maximum energy generation is known as Maximum Power Point Tracking (MPPT). The converter is used to change the apparent DC bus voltage seen by the generator. Thus by controlling the DC converter the terminal voltage of the PMSG is adjustable in order to maximize power production. For maximum power transfer in all wind speeds, the converter must be able to reduce PMSG terminal voltage in low wind speeds, and increase in high wind speeds [5, 6]. Thus, the recommended converter for this type of application must have boost voltage characteristics.

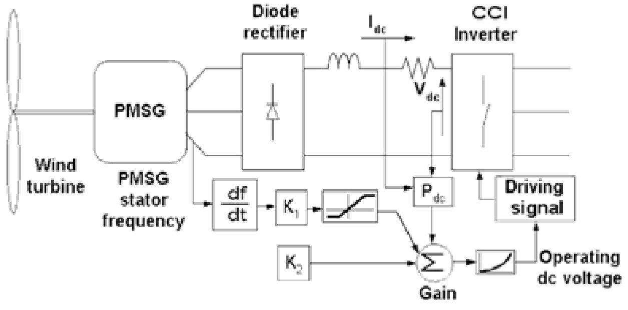
V. PMSG MAXIMUM POWER EXTRACTION CONTROL SCHEMES

optimum wind energy extraction is achieved by running the wind turbine generator (WTG) in variable-speed variable-frequency mode. The rotor speed is allowed to vary in sympathy with the wind speed by maintaining the tip speed ratio to the value that maximizes aerodynamic efficiency. In order to achieve this ratio, the permanent-magnet synchronous generator (PMSG) load line should be matched very closely to the maximum power line of the wind turbine generator. In such a case, a good matching exists between the generator and the load for the best performance of the system, as well as the maximum utilization of the wind driven PMSG. However, the recent advancements in power electronics and control strategies have made it possible to regulate the voltage of the PMSG in many different ways.

During the last few decades, many different maximum power point tracking (MPPT) control strategies have been developed [1], [2]. This enabled the selection of the optimal MPPT for each WECS project. In addition, a number of theoretical studies have been made with the aim to establish the energy capture benefits associated with variable speed operation of WECS. A review of the recent publications show there is very little agreement on the gain in projected energy [3]. It must be mentioned here that all techniques of maximum energy capture in WECS so far have been based on signals available from an anemometer .For maximum power extraction from the wind, the speed of the rotor can be adjusted by controlling the difference between the electrical output power and the aerodynamic power captured.

Method Number	Details of Method	Wind Speed Targeted m/sec	Sampling Time
1	MPPT controller with anemometer	4-12	1 sec
2	Proposed frequency derivative and "power-mapping" Controller	4-12	1 sec
3	5 speed -30sec sampling	6,7,8,9 and 10	30 sec
4	5 speed -60sec sampling	6,7,8,9 and 10	60 sec
5	3 speed -60sec sampling	7,8 and 10	60 sec
6	Fixed Voltage	9	-

Lower to medium wind speed, with a power converter, the electrical output power can be controlled by varying the electrical torque applied to the turbine and, therefore, the rotor speed. As the wind speed increases toward the higher wind speed region, the power generated by the turbine also increases. Once the maximum rating of the turbine is reached, mechanical power shedding is usually invoked to protect the system. Protection mechanism can include passive pitch control, passive yaw control, and dump load.



In the proposed sensor less scheme, the inverter input operating voltage is determined by a “power-mapping” technique .The “power-mapping” technique is similar to the one-dimensional lookup table with one input $(P_{dc})$and one output (V_{dc}) (estimated voltage). The lookup table contains the maximum power versus dc

.The block diagram shown in Fig. is the preliminary design of the sensor less WECS-controlled system. The control system consists of two signal-tracking loops, namely the “power-mapping” loop and “alternator frequency derivative” loop. The tracking signals required for both loops are the output power from the WECS that is transferred to the dc link and PMSG stator frequency. The current control inverter usually has the flexibility to operate over a wide range of dc input voltages.

1) MPPT With Anemometer: Fig. shows the overall control scheme of the WECS with anemometer sensor. A proportional integrator (PI) controller is used to derive the maximum possible power from the wind at a different wind speed. The anemometer provides the wind power reference to the MPPT controller. This reference is compared with the power extracted from the WECS, and hence, the input operating dc voltage reference can be derived. This signal is fed into the current control loop of the CCI inverter and gives the instantaneous driving signal. This driving signal adjusts the torque output, hence, the wind turbine rotor speed.

Control of Generator-Side Converter In wind turbine PMSG systems, three system variables need to be strictly controlled [6]: (1) the optimal power generated by the PMSG at different wind speed levels; (2) the active and reactive power injected into the grid; (3) the DC bus voltage of the back to back converter. Figure shows a direct-drive wind turbine PMSG fed by a back-to-back converter. In this system, the generator-side converter regulates the speed of the PMSG to implement the MPPT control. Meanwhile, the grid-connected converter controls the active and reactive power injected into the grid DC/AC.

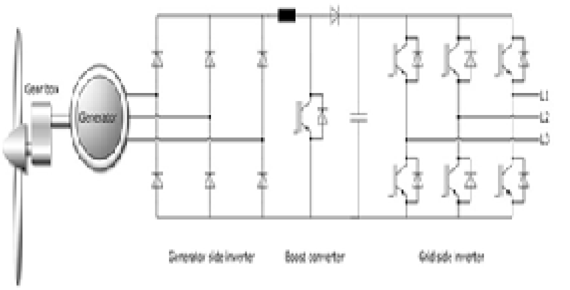
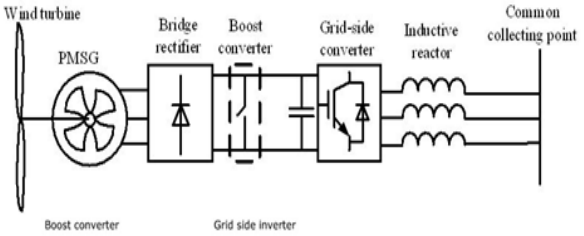


Fig.5: Direct-drive PMSG system

Control of Grid-Side Converter

In direct-drive PMSG wind turbine systems, grid-connected converters play an important role in transforming the DC power to AC power. As introduced earlier in, there are three system variables that need to be strictly controlled. Namely, these variables are the speed of the PMSG, the DC bus voltage, and the complex power (active and reactive power) injected into the grid [6]. As the generator
side converter controls the speed of the PMSG, the grid-side converter regulates the DC bus voltage while controlling the active power and reactive power injected into the grid. In this research, the control approach for the grid-side converter is analyzed. This converter is assumed to be operating on the basis of the principle of the space vector pulse width modulation (SVPWM), which will be elaborated on here. Furthermore, the simulation results will be obtained and given here to validate the proposed control strategy.
As stated earlier, the main objective of the grid-side converter control is to regulate the active and reactive power



Though MPPT achieved the generated power fluctuate. If the generator is connected to grid it is injecting fluctuating power to grid. So super capacitor are used to smooth the fluctuating power.

VI. FUTURE SCOPES

Minimization of Grid injected Power fluctuation Super capacitor is a double layer capacitor; the energy is stored by charge transfer at the boundary between electrode and electrolyte. The amount of stored energy is function of the available electrode and electrolyte surface, the size of the ions, and the level of the electrolyte decomposition voltage.

Super capacitors are constituted of two electrodes, a separator and an electrolyte. The two electrodes, made of activated carbon provide a high surface area part, defining so energy density of the component. On the electrodes, current collectors with a high conducting part assure the interface between the electrodes and the connections of the super capacitor. The two electrodes are separated by a membrane, which allows the mobility of charged ions and forbids no electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other [5, 12].

An ultra capacitor, also called a super capacitor, is an electrical component capable of holding hundreds of times more electrical charge quantity than a standard capacitor. This characteristic makes ultra capacitors useful in devices that require relatively little current and low voltage. In some situations, an ultra capacitor can take the place of a rechargeable low-voltage electrochemical battery. Advantage of SCESS is that the super capacitor has a very rapid dynamic response and high power density. So, it is able to switch from the maximum charging current to the maximum discharging current or the vice versa. SCESS operates for smoothing a fluctuating wind power during short-term. An excellent example of the use of an ultra capacitor can be found in so-called electrical smart meters. These devices, unlike their electromechanical counterparts, store information about home and business electrical power and energy consumption, and contain no moving parts. In the event of a power failure, an ultra capacitor allows the meter to send a final status communication to the utility company, preventing data loss and the confusion that could result. While a rechargeable backup battery can serve the same purpose, most electrochemical batteries fail at extremely low temperatures, such as commonly occur in the winter in much of the United States and virtually all of Canada. Ultra capacitors keep working at temperatures far below freezing. Ultra capacitors can be found in emergency radios and flashlights. The ultra capacitor charges up with the help of a miniature direct-current (DC) generator that the user can manually operate for a couple of minutes by turning a small crank. Once the ultra capacitor has acquired a full charge, the device can function for quite awhile (in some cases over an hour) before it needs a recharge.

This research has proposed a control method for maintaining the energy level for a SCESS coupled with a wind generator to stabilize wind power output. In order to mitigate the fluctuating output power, SCESS and wind power simulator has been developed. SCESS has been applied to smooth for short-term fluctuating power and provided a high quality power to grid system.

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