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Complete Analysis of Doubly Fed Induction Generator Wind Turbine-Maximum Power Tracking Characteristics

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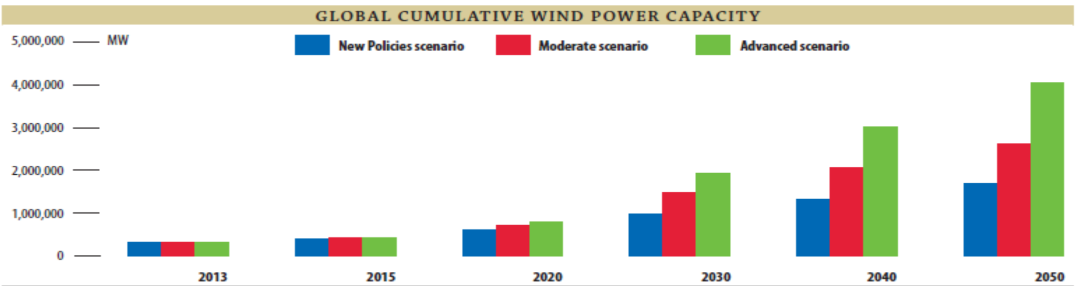
Abstract: **Energy is a necessary and essential ingredient of socio-economic development and economic growth. There are various sources of energy, out of which, wind energy is free and clean renewable source of energy. Wind is caused by differential heating of earth's surface by the sun. Greenhouse gas emission per unit of wind energy are approximately 90% less than the emission from conventional fossil fuel power sources. It has been estimated that roughly 10 millions MW of energy are continuously available in the earth's wind. Now, a days various types of wind turbines are used for producing electrical energy. Out of which DFIG wind turbine is a variable speed wind turbine. Before, using a wind farm consumer should know about its power drawn capacity of DFIG wind turbine. In this paper, there is a complete analysis of 12 MW wind farm connected with DFIG wind turbine maximum power tracking characteristics curve followed by the simulation model results w.r.to voltage, current and generated power (P and Q).After that graphical results are compared with its mathematical evaluation with its aerodynamic equation. Simulations are done under MATLAB/SIMULINK.**

Keywords: **Wind energy, doubly-fed induction generator- wind turbine, wind farm, tracking characteristics.**

I. INTRODUCTION

Wind power has now firmly established itself as a main stream option for new electrical generation. The most remarkable recent development is that in an increasing number of markets, wind power is the least cost option when adding new generation capacity to the grid, and prices continue to fall down. There are now commercial wind power installations, in more than 90 countries with total installed capacity of 318 GW at the end of 2013, providing about 3% of global electricity supply last year.



		2013	2015	2020	2030	2040	2050
New Policies scenario							
	MW	318,128	396,311	610,979	964,465	1,324,814	1,684,074
	TWh/a	620	972	1,499	2,535	3,482	4,426
Moderate scenario							
	MW	318,128	413,039	712,081	1,479,767	2,089,261	2,672,231
	TWh/a	620	1,013	1,747	3,889	5,491	7,023
Advanced scenario							
	MW	318,128	420,363	800,615	1,933,989	3,024,473	4,042,475
	TWh/a	620	1,031	1,964	5,083	7,948	10,624

Fig.1 Global Cumulative Wind Power Energy Report 2014

In recent years, most wind turbines operated at fixed speed when producing power. In a start up sequence the rotor may be parked (held at stopped),and on the release of the brakes would be accelerated by the wind until the fixed speed was reached. This is the main drawback of fixed speed wind turbine, that only fixed speed wind was able to generate power.[1]

Subsequently, variable speed operation was introduced. This allows the rotor and speed to be matched, and rotor could maintain the best flow geometry for maximum efficiency. Now a days, DFIG wind turbine is used as a variable speed wind turbine .DFIG abbreviated as doubly fed induction generator wind turbine is a wound- rotor induction generator.[2]

II. DOUBLY - FED INDUCTION GENERATOR

The doubly-fed induction generator (DFIG) is most used by the wind turbine industry. As shown in Fig.2, the DFIG is consist of wound rotor induction generator with the stator windings connected directly to the grid and the rotor windings connected to a back to-back AC-DC-AC voltage source converter [3]. The stator voltage is applied from the grid and the rotor voltage is applied from the power converter.

The stator output power into the grid all the time, while the rotor is feeding power into the grid when in over synchronous operation and absorbs power from the grid when in the sub-synchronous operation [4]. The DFIG based wind turbine allows variable speed operation over a large but still restricted range limited by the scale of the power electronics converter and its controllers.

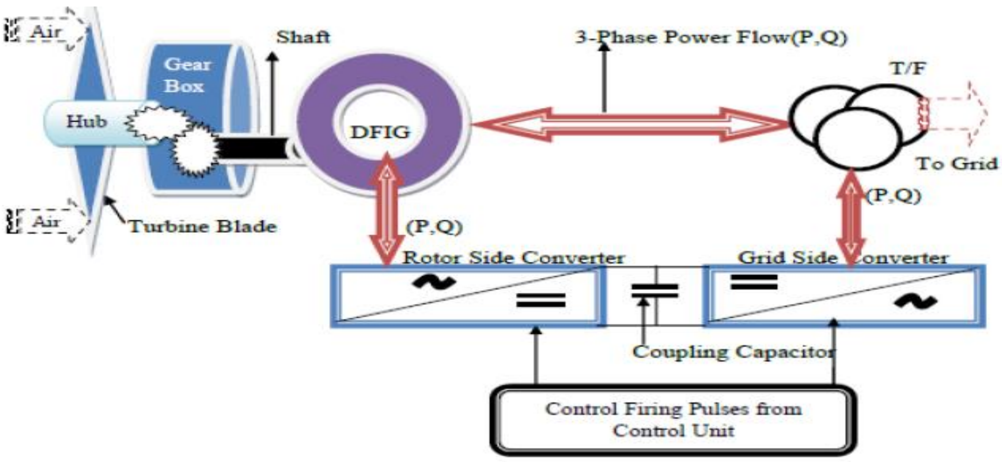


Fig.2 DFIG Wind Turbine

The power electronics converter used for DFIG based wind turbine is comprises of two IGBT converters: rotor side converter and grid side converter with a DC-link connection.

The rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor. DFIG based variable speed wind turbines are highly controllable, allowing maximum power capture over a large range of wind speeds, typically of ±40% around the synchronous speed. Furthermore, the active and reactive power control is decoupled by in dependently controlling the rotor currents via the power electronics converters. There are following advantages listed for DFIG based WECS [4-6]:

- In DFIG, Converter system provides reactive power compensation and smooth grid integration.
- Converter Rating is only 25%-30% in DFIG as compared to 100 % of total nominal power of the generator.
- Wider range of variable speed of approximately ± 30% around synchronous speed.

III. ERODYNAMIC CONVERSION OF WIND TURBINE

Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the WT. For steady-state calculations of the mechanical power from a wind turbine, the so called C_p (λ, β)-curve can be used. The mechanical power, P_{mech}, is described as:-

$$P_{mech} = \frac{1}{2} C_P(\lambda, \beta)\rho A V^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where,

Cp: Turbine power coefficient.

ρ: Air density (kg/m^3).

A: Turbine sweeping area (m^2).

V: Wind speed (m/s).

λ: Tip speed ratio of the wind turbine which is given by the following equation

Where, $\lambda = \frac{r_m \, \omega_r}{v}$……………………..(2)

Where r_m is the turbine rotor radius, ω_r is the angular velocity of turbine (rad/s).

$$C_P(\lambda, \beta) = 0.5176\left(116 * \frac{1}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_i}} + 0.0068\,\lambda \quad \ldots\ldots(3)$$

With, $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}$ ……………… (4)

IV. MAXIMUM POWER TRACKING CURVE

The wind turbine always operates with different dynamics, from minimum wind speed to maximum wind speed, and the operating regions of the wind turbine can be illustrated by their power curve shown as in Figure 4. Three wind speeds and two operation modes are shown in this power curve, and their definitions are as given below [7] [8]:

- **Cut-in speed**: The cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 0 and 5m/sec for most turbines.
- **Rated speed:** The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. At wind speeds between the cut-in speed and the rated speed, the wind turbine will operate at the "maximum power point tracking (MPPT) mode", and the output power of a wind turbine will increase as the wind speed increases.
- **Cut-out speed:** At very high wind speeds, typically between 15 and 22m/sec, most wind turbines cease power generation and are shut down for protection purposes. The wind speed at which shut down operation occurs is called the cut-out speed. When the wind turbine experiences high wind speed, the mechanical part of the wind turbine may be damaged, and hence having a cut-out speed is a safety consideration. When the wind speed drops back to a safety level, the wind turbine operation usually resumes.

V. PROBLEM STATEMENT

Before using a DFIG wind turbine, customer should know the maximum capacity of the wind turbine using in the grid. The first duty of the power engineer is to check the data which is provided by the manufacturer and then, compare that turbine follows the maximum power tracking characteristic curve of the wind turbine.

Since, wind speed is not constant throughout the day .So, there is various problem arises while using the wind farm. Based on the following researches, while using a wind turbine which is connected with a grid following problem should arises.-

Problem Statement #1
Develop a simulation model of wind farm.

Problem Statement #2
Calculate the maximum power extraction of wind turbine by using aerodynamic equation of wind turbine.

Problem Statement #3
Compare the graphical simulation results with the aerodynamic equation.

Problem Statement #4
Develop a maximum power tracking curve using the simulation result and aerodynamic equation.

VI. RESEARCH APPROACH

This research deals with the three operations:-

Firstly, developing the simulation model of a 12 MW wind farm connected with DFIG wind turbine and simulation results based on wind turbine voltage, current, generated active and reactive power, DC bus voltage and turbine speed.

Secondly, the graphical results were compared with the aerodynamic equation which shows the graphical model follow the maximum power tracking curve.

Finally, developing a maximum power tracking curve of a 12 MW wind farm connected with DFIG wind turbine (Turbine speed v/s turbine output power).

VII. SIMULATION MODEL

A 12-MW wind farm consisting of eight 1.5 MW wind turbines connected to a 25-kV distribution system exports power to a 110-kV grid through a 10-km, 25-kV feeder. A 2250V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200-kW resistive load is connected on the same feeder at bus B25. Both the wind turbine and the motor load have a protection system monitoring voltage, current and machine speed.

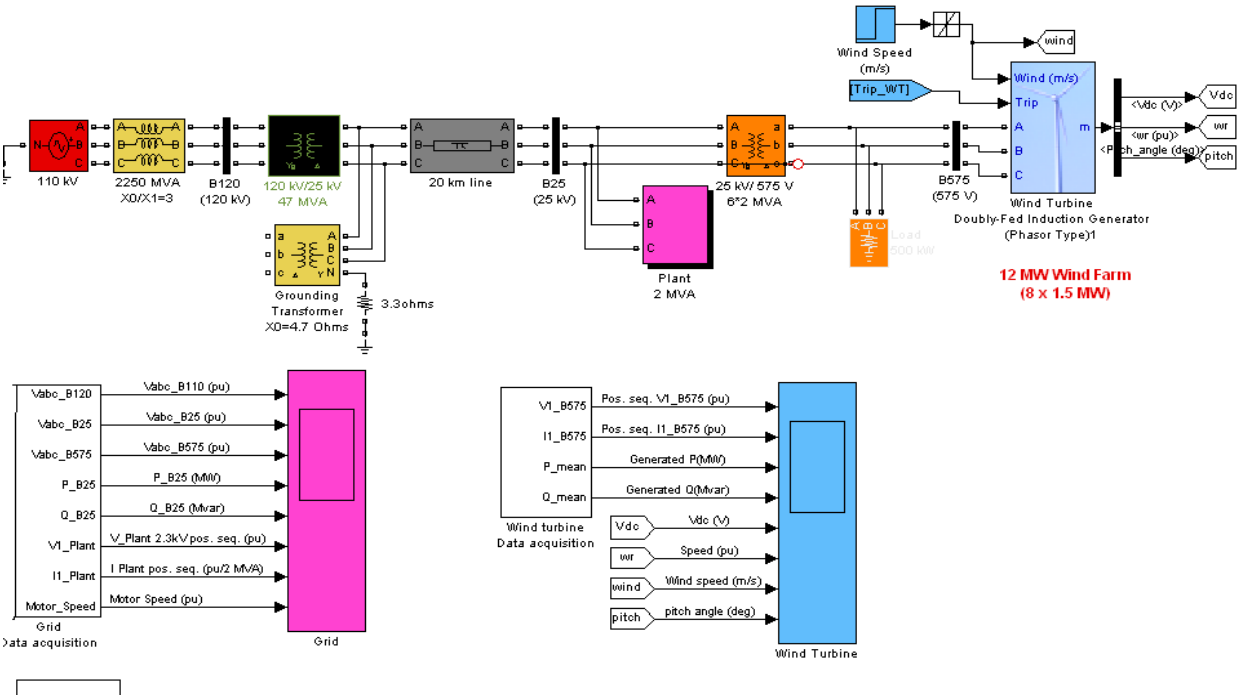


Fig.3 12MW wind farm connected with DFIG

VIII. SIMULATION RESULTS

In the "Wind speed" step block specifying the wind speed.

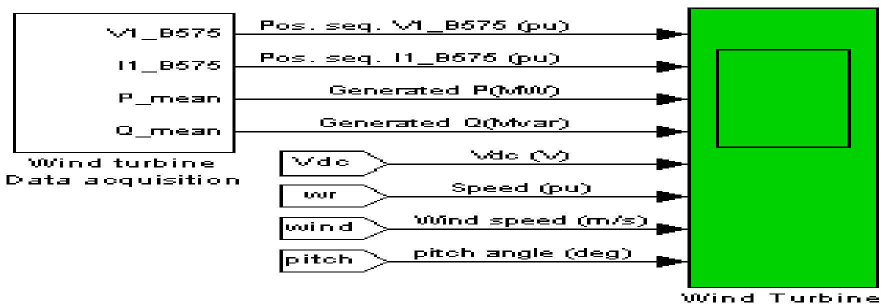


Fig.4 wind turbine output block

(A) Turbine Response To Change In Wind Speed:-

Initially ,the wind speed is set at 6m/s, then at t=5s,wind speed suddenly increases at 15m/s. Start simulation and observe the signals on the "wind turbine" scope monitoring the wind turbine voltage, current, generated active and reactive power, DC bus voltage and turbine speed.

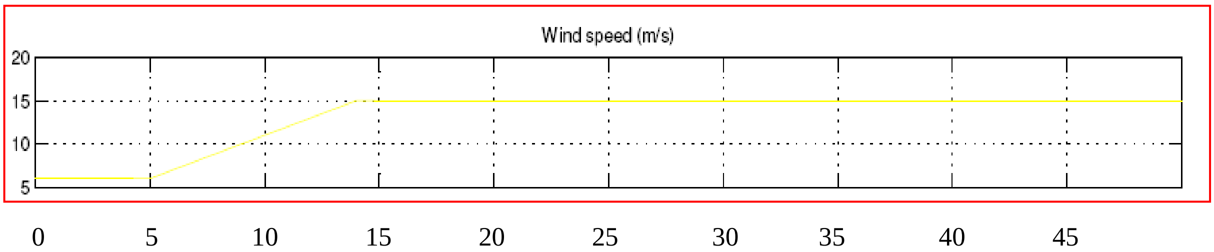


Fig.5 wind speed v/s time

(B) TURBINE SPEED:-

Over that time the turbine speed increased from 0.8 to 1.21PU.

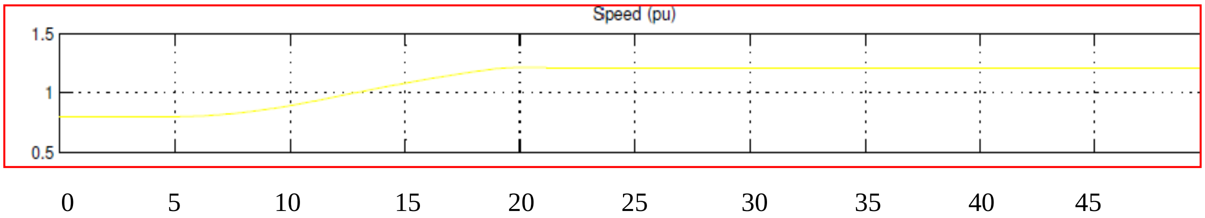


Fig.6 turbine speed v/s time

(C) GENERATED ACTIVE POWER:-

At t=5sec, the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 12MW in approximately.

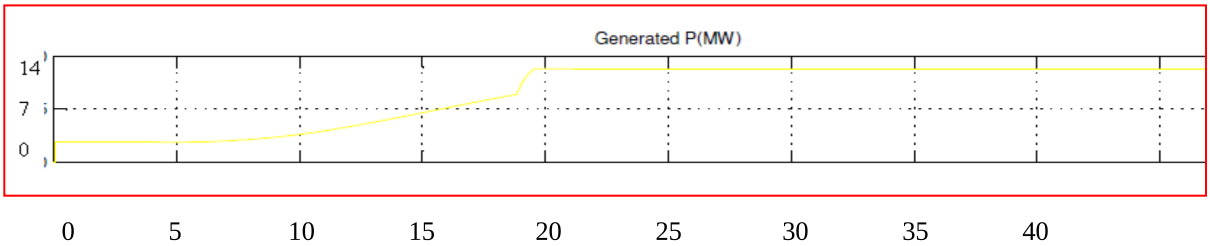


Fig.7 Generated power v/s time

(D) GENERATED REACTIVE POWER:-

The reactive power is controlled to maintain 1 pu voltage. At nominal power, the wind turbine absorbs 0.67 Mvar (generated Q=-0.67 Mvar) to control voltage at 1 pu.

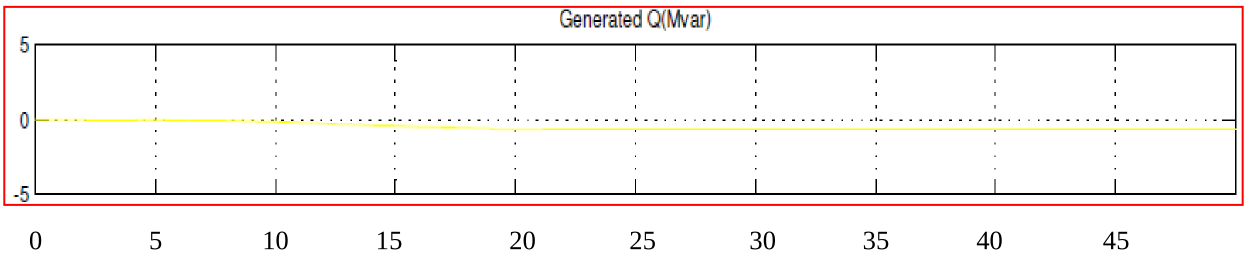


Fig.8 Generated power v/s time

PITCH ANGLE:-

Initially, the pitch angle of the turbine blades is zero degree and the turbine operating point follows the red curve of the turbine power characteristics upto point D. then the pitch angle is increased from 0 deg to 0.76 deg in order to limit the mechanical power.

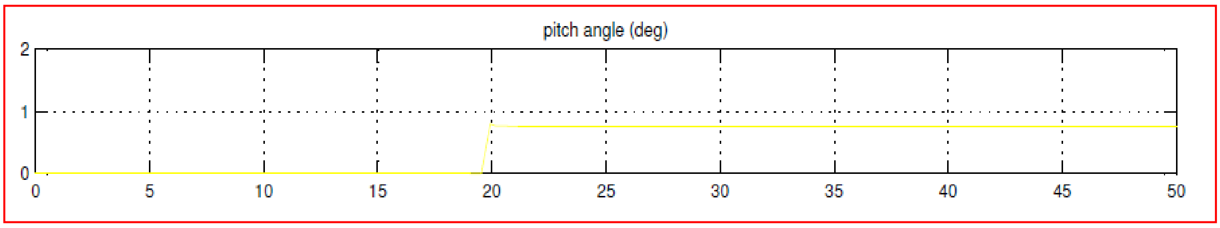


Fig.9 pitch angle v/s time

Table1.Tabular Data of Graphical Data

TIME(in sec)	WIND SPEED	TURBINE SPEED	GENERATED POWER P(in MW)	GENERATED POWER Q(in MVAR)
0-5	6	0.80	2	0.68
5-10	7	0.82	2	0.68
	8	0.83	2.5	0.68
	9	0.85	3	0.68
	10	0.9	4.5	-0.68
	11	0.95	5.7	-0.68
	12	0.9	6.5	-0.68
10-15	14	1.2	10	-0.68
15-20	15	1.21	12	-0.68

(E) POWER COFFICIENT (C_P)V/S LAMBDA(λ)

Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the WT. For steady-state calculations of the mechanical power from a wind turbine, the so called C_p (λ, β) curve can be used.

The following curve shown in fig. shows the relationship between C_p and λ, with pitch angle zero degree.

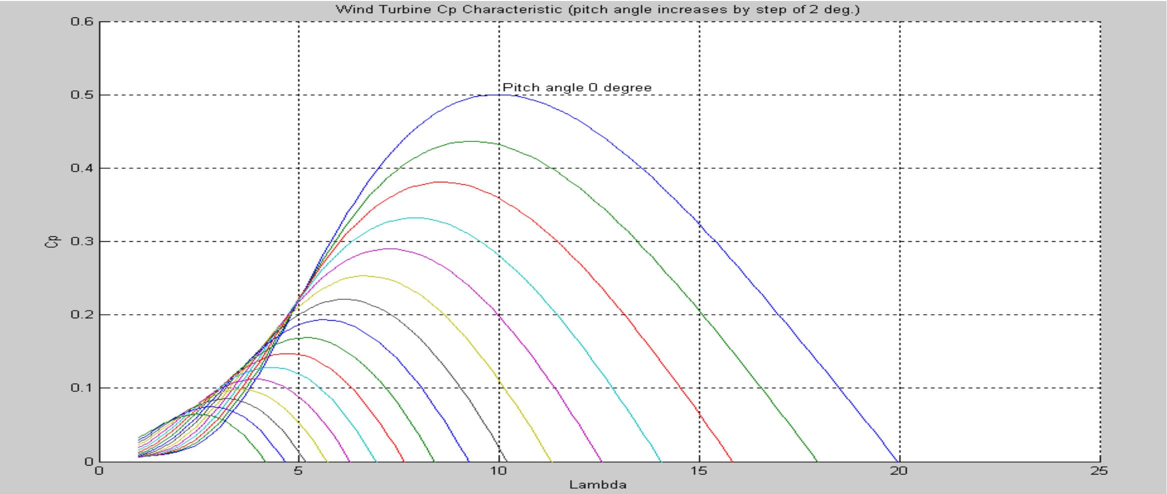


Fig.10 C_P V/S λ graph

Table 2. Different Values Of Lambda And Power Cofficient In Different Wind Speed

WIND SPEED(in m/sec)	λ	C_P
6	20	0.5
7	17	0.43
8	15	0.38
9	13	0.29
10	11	0.25

(H) C_P,. λ AND POWER W.R.TO TIME

Following curve shows that the variation in power coefficient, lambda and power with respect to wind speed. It has been shown with the graphical data that the maximum value of C_P is 0.5.

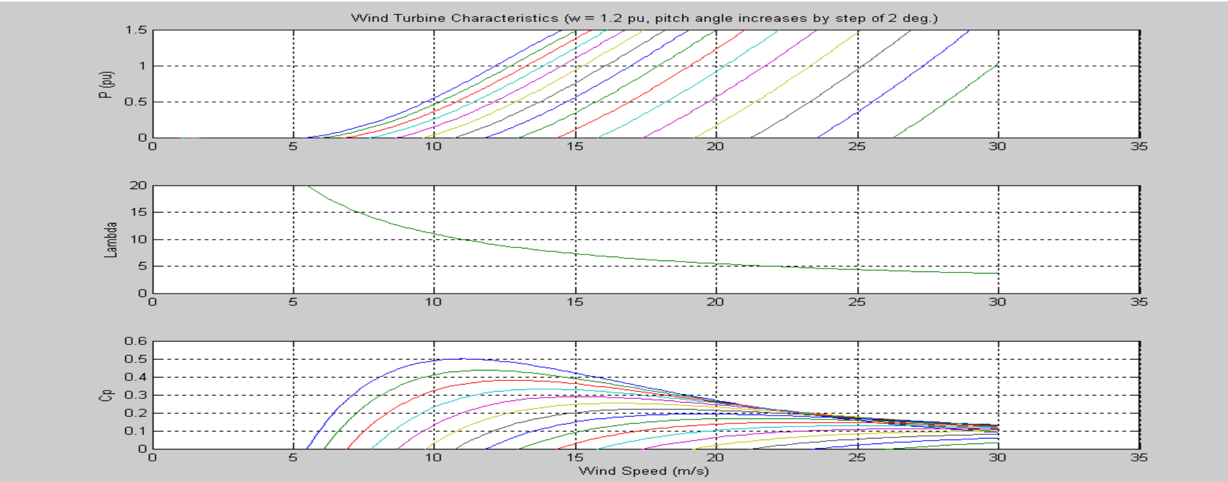


Fig.11 C_P ,λ. And power w.r.to time

IX. MATHEMATICAL CALCULATION

Aerodynamic Model

A WTGS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. The conversion takes places by using two devices. The first one is the extraction device, which harvests the mechanical power by the wind stream turning the wind turbine rotor. The other one is the generator which transforms the rotational mechanical power to electrical power. The relationship between the mechanical input power and the wind speed passing through a turbine rotor plane can be written as follows [12]:

$$P_{mech} = \frac{1}{2} C_P(\lambda, \beta)\rho A V^3$$

Where,

Cp: Turbine power coefficient.

ρ: Air density (kg/m^3).

A: Turbine sweeping area (m^2).

V: Wind speed (m/s).

λ: Tip speed ratio of the wind turbine which is given by the following equation

Where, $\lambda = \frac{r_m \, \omega_r}{v}$

Where r_m is the turbine rotor radius, ω_r is the angular velocity of turbine (rad/s).

$$C_P(\lambda,\beta) = 0.5176\left(116 * \frac{1}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_i}} + 0.0068\,\lambda$$

With, $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}$

(i) calculation of λ :-

$$\lambda = \frac{r_m\,\omega_r}{v}$$

Where, r_m is the turbine rotor radius,=33 m

ω_r is the angular velocity of turbine (rad/s).=2fπ

Table 3. Wind speed v/s lambda

Wind speed	λ
6m/s	20
7m/s	18
8m/s	15
9m/s	13
10m/s	11

- $C_P(\lambda,\beta) = 0.5176\left(116 * \frac{1}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_i}} + 0.0068\,\lambda$

When, λ =8.1,β=0

- $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}$
- $\frac{1}{\lambda_i} = \frac{1}{8.1 + 0.08*0} - \frac{0.035}{1+0}$

  $\frac{1}{\lambda_i} = 0.088$
- $C_P(8.1,0) = 0.5176(116 * 0.088 - 0.4 * -5)e^{-21*0.88} + 0.0068 * 8.1$
- $C_P(8.1,0) = 0.48$
- $P_{mech} = \frac{1}{2} C_P(\lambda,\beta)\rho A V^3$
- $P_{mech} = \frac{1}{2} 0.48 * 1.225 * 3421.19 * (15)^3$
- P_{mech} =1194676 watt
- $P_{mech} = 11.94476\text{MW} = 12\text{MW}$

X. COMPARISON TABLE OF GRAPHICAL METHOD AND MATHEMATICAL ANALYSIS

TABLE 4. COMPARISON TABLE OF C_P, λ W.R.TO DIFFERENT WIND POWER

WIND SPEED(in m/sec)	λ	C_P(GRAPHICAL)	C_P(MATHEMATICAL)
6	20	0.5	0.48
7	17	0.43	0.40
8	15	0.38	0.35
9	13	0.29	0.25
10	11	0.25	0.23

Hence, with the help of above graphical and mathematical calculation and the study of maximum power tracking characteristic of DFIG wind turbine, above 12 MW wind farm follows the following maximum power tracking curve.

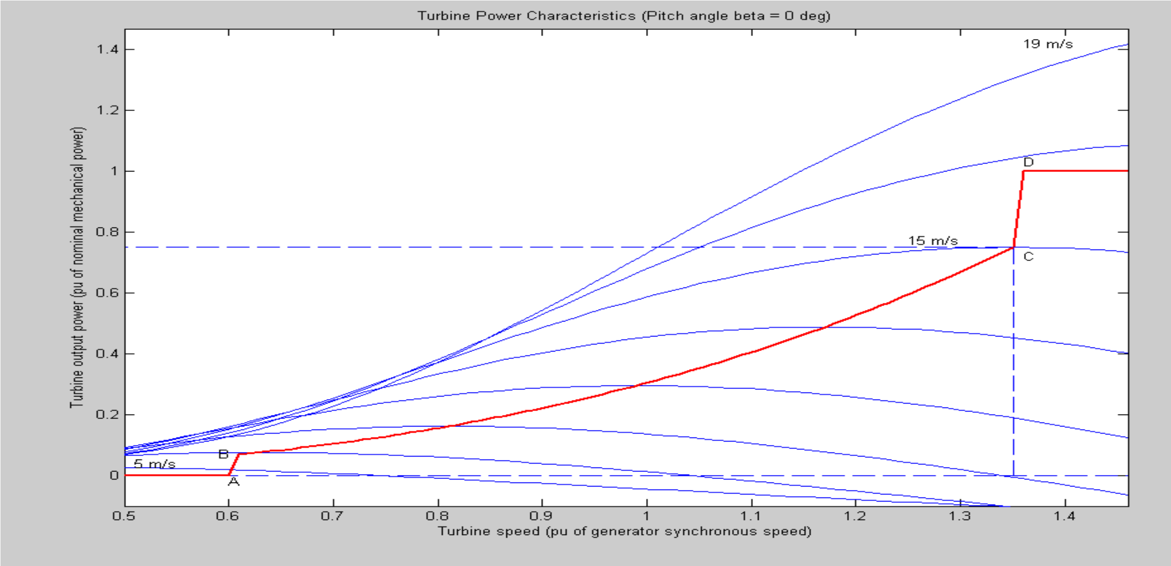


Fig .12 maximum power tracking curve

Point A-B:- Cut-in speed.
Point B-C:-Rated speed.
Point C-D:-Cut-off speed.

XI . CONCLUSION

Maximum power extraction from wind energy system became an important research topic due to the increase in output energy by using this technique. This paper shows that the maximum power can be extracted with the help of aerodynamic equation of wind turbine. Hence, followed the maximum power tracking curve.

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