Maximum Power Extraction from Wind Turbine using Optimum Generator Speed Calculation

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Abstract— The aim of this research is to extract maximum power with fixed point calculation, the developed method of maximum power extraction is based on optimal speed calculation of the generator. Here we are going to use PMSG (Permanent magnet synchronous generator) as WTG (Wind Turbine Generator), three phase bridge rectifier for converting ac to dc and boost converter for converting unregulated dc to regulated dc voltage. This control scheme become possible with the help of measuring wind speed then calculating the optimal generator speed and that optimal generator speed will be used as a control signal which will be applied to the boost converter to vary the dc side voltage and control the generator speed according to the optimal speed so that the optimal speed of the generator will be tracked properly in which we will get the maximum power from the generator. The prototype of the WTG with the combination of the mentioned equipment is simulated with the help of MatLab/SIMULINK software.

Key words: Wind Turbine Generation System, Maximum Power Extraction, Wind Energy, MPPT, PMSG, Permanent Magnet Synchronous Generator

I. INTRODUCTION

The daily increment in using convention or non-renewable energy will lead us to a much polluted environment in future. Thus, the conventional non-renewable sources are replace by developed, clean and renewable energy sources such as solar and wind energy.

The amount of conventional energy all over the world is limited and becoming scarce after centuries of exploitation. Most of these energy supplies will be depleted in the future if the current use of these resources continues at the present rate. That is why the interest increase in the renewable energy which wind energy is one of the main renewable energy sources because of its advantages its cost effective, pollution free, and safety. It has proven to be the best choice among the renewable energy sources [1] which now the installation of wind energy is day by day increasing. Now the average annual growth rate of wind turbine installation is around 30% during last 10 years [2] and by the end of 2006 the global wind electricity generating capacity has increased to 74223 MW from 59091 MW in 2005[3].

wind turbine concepts can be classified into fixed speed, and variable speed.[2] in fixed speed the efficiency will reduce because our turbine may not operate at maximum power point so the output power may be reduced but the Variable speed system have several advantages such as yielding maximum power output while developing low amount of mechanical stress compared to constant speed systems so we have used variable speed concept of wind turbine in this paper [4].

As we know the wind is varying the output power is also varying but in each wind speed there will be a maximum power point in that point we can get maximum power [5] that is why it is very important to use some control topology to get to that point as shown in Fig. 3 To track this point at variable wind speed various MPPT (Maximum power point tracking topologies are used and generally they can be classified into mechanically pitched control as in [6] and electrically by electronics converter.

Here we will be using PMSG (permanent magnet synchronous generator) because It offers better performance due to higher efficiency and less maintenance since it does not have rotor current and can be used without a gearbox because of its lower speed operation which also implies a reduction of the weight of the nacelle and a reduction of costs [8,9].

Till now a significant amount of research has been performed on MPPT for variable speed wind Turbines [7]. Generally MPPT are based two type control scheme

The optimum parameters of the speed of turbine or generator and optimum tip speed ratio
1) The electronic converters control
2) A lot of research has been done on the MPPT of Wind Turbine so here I will be reviewing some of it:

In [5] the control is done by estimating rotor speed of PMSG from dc voltage, dc current and some known parameters.

In [8],[9],[10] they calculated the \(\lambda_{opt}\), \(\omega_{opt}\), \(C_p\) (\(\lambda_{opt}\)) then at last \(P_{opt}\). Which are the optimal tip speed ratio, generator optimal speed, optimal power coefficient, and Power optimal respectively In [10] wind turbine speed is controlled through pitch or movable blade means mechanically controlled which is very costly than the electronically controlled


In [12] a cascaded H-bridge multilevel inverter (CHB MLI) is proposed for the DC/AC conversion Which will increase the switches and losses will be increased too.

In [13] multilevel clamped (NPC) converter is used for the Wind turbine PMSG in this type again with increasing switches the switching in the circuit and cost will increase which is not suitable. For a small wind turbine.

In [5],[7],[9],[10],[12] all these MPPT are based on mechanical parameters of wind turbine, my purposed control scheme is also base on mechanical parameter but in above reviewed most of them using more sensor and measurement devices which will reduce accuracy and increase the cost and maintenance of the devices here I will...
use only one sensor for the measuring of wind and from that I will calculation the optimal speed of the generator.

The proposed MPPT control scheme general block diagram is shown in Fig.2 which is a very easy and cheaper way of controlling the wind speed and extracting the maximum power out of it.

And in [11],[13] had various electronically controlled topology which is based on the voltage and current measurement then calculating electrical power and tracking the maximum power point through slope principle the drawback of these control scheme it can’t reach to stable value it is always varying near the maximum point and also this type of control work for a small wind turbine.

Here my proposed MPPT Control Scheme is different from the above reviewed research paper here I will be using the maximum power coefficient value and the measured wind speed to get optimal speed of the wind generator and then by multiplying it with the adjusting factor duty cycle factor I will get the proportional duty cycle for the boost converter and that duty cycle will vary the voltage of the boost converter accordingly so that the generator rotate at its optimal value, no matter what the wind speed is it will be optimally rotating and getting giving us maximum power.

The advantage of this propose topology is that it gives very good control at maximum point because of fixed calculation of optimal value of the generator speed and also this control scheme can be used for large wind turbine generator too.

This control scheme has higher reliability, low complexity, lower cost and easy to implement.

Fig. 1: General Block Diagram of PMSG Wind Turbine With MPPT Control

II. MECHANICAL POWER OF WIND TURBINE

Available Power in the wind is calculated as:

$$ P_{\text{wind}} = \frac{1}{2} \rho AV^3 $$

Here $P_{\text{wind}}$ is the available power in the wind, $A$ is the swept area of the wind turbine which is equal to $A = \pi R^2$, $V$ the wind speed in [m/sec] and $\rho$ is the air density which varies with air pressure and temperature here I will be using $\rho = 1.225 \text{ kg/m}^3$ in my project. [16]

Power Coefficient can be:

$$ C_p = \frac{P_{\text{mech}}}{P_{\text{wind}}} $$

So from the (2) we can find the Mechanical power of the wind turbine or the extracted power from the wind by wind turbine as:

$$ P_{\text{mech}} = C_p \times P_{\text{wind}} $$

$$ P_{\text{mech}} = C_p \times \frac{1}{2} \rho AV^3 $$

Here $C_p$ is the power coefficient and is equal to,

$$ C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{-\frac{c_5}{\lambda_i} + c_6 \lambda} $$

Here $\frac{1}{\lambda_i}$ is equal to:

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

Here the coefficients are $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, and $c_6 = 0.0068$, and the relation between $C_p(\lambda)$ while $\beta = \text{constant}$ is illustrated in Fig.1 [18]

Fig. 2: Relation of Power Coefficient VS TSR

III. ELECTRICAL POWER OF PMSG

PMSG circuit diagram for single phase is illustrated in Fig.3 which Phase Voltages of PMSG can be derived as:

$$ V_a = r_i i_a + \frac{d}{dt} \lambda_a $$

$$ V_b = r_i i_b + \frac{d}{dt} \lambda_b $$

$$ V_c = r_i i_c + \frac{d}{dt} \lambda_c $$

The flux linkages equations are expressed as follows,

$$ \lambda_{abc} = L_{abc} i_{abc} + \lambda_{m} \left[ \sin \left( \theta_c - \frac{2\pi}{3} \right) \right] $$

$$ \sin \left( \theta_c - \frac{2\pi}{3} \right) $$
In the above equation $\lambda_m'$ denotes the amplitude of the flux linkage established by permanent magnet. And $L_s$ is the stator self-inductance.

The Torque and Speed can be related by electromechanical motion equation:

$$T_{mech} = \frac{1}{2} (T_e - T_L) - B_m \omega_{rm}$$

Where, $J$ is the inertia, $B_m$ is the approximated mechanical damping due to friction and $T_L$ is the load torque.

For the generation of electricity through any power plant prime mover is necessary to drive the generator. In wind generation system, Wind Turbine is the Prime Mover of the Generator. At steady estate, the electromechanical torque of the machine should balance the mechanical torque on rotor shaft, created by the wind turbine in addition with the mechanical losses as follows,

$$T_{mech} = T_{em} + T_{loss}$$

The power balance equation can be given as

$$P_{mech} = P_{em} + P_{loss}$$

Where $P_{mech} = T_{mech} \omega_{syn}$ is the mechanical power supplied by the wind turbine.

$P_{em} = T_{em} \omega_{syn}$ is the power of the generator, $P_{loss} = T_{loss} \omega_{syn}$ is the mechanical power loss of the system. The generated power can be written as:

$$P_{em} = T_{em} \omega_{syn} = 3E_1 I_1 \cos(\phi_{Ea1})$$

And where, $\phi_{Ea1}$ is the angle between phasors $E_a$ and $I_a$.

IV. AC –TO- DC UNCONTROLLED RECTIFIER

As it is visible from the name uncontrolled rectifier is a converter that uses uncontrolled device for converting like diodes to supply a dc circuit from an ac source. An uncontrolled rectifier gives a fixed dc output voltage for a given ac supply. Fig.4 shows the circuit of a three phase, full-wave diode bridge rectifier.

The output Voltage of the Rectifier:

$$V_{dc} = \frac{1}{\sqrt{2}} V_{LL} \cos(at) d(at)$$

$$V_{dc} = \frac{3\sqrt{2} V_{LL} \cos(at) d(at)}{\pi}$$

Here $V_{LL}$ is line to line voltage of PMSG and $V_{dc}$ is output voltage of the Rectifier. [14], [15]

V. DC TO DC BOOST CONVERTER

Here Boost Converter Convert Unregulated DC Voltage to Regulated DC Voltage Circuit Diagram is shown in Fig. 5

![Fig. 5: Circuit Diagram of Boost Converter](image)

There are two operational Mode 1- switched on

mode of operation 2- switched off mode of operation as illustrated in Fig. 3.6:

![Fig. 6: The Boost Converter: (A) Switch On (Mode 1); (B) Switch Off (Mode 2).](image)

The output voltage, Duty Cycle, Capacitor and Inductor Values can be calculated as:

$$\frac{V_o}{V_{dc}} = \frac{1 - D}{1 - D}$$

$$D = \frac{V_{ot}}{V_{t}}$$

$$C = \frac{D \cdot V_{d} \cdot V_{c}}{\Delta V_{c}}$$

$$L = \frac{D \cdot V_{d} \cdot \Delta l}{\Delta V_{c}}$$

VI. PROBLEM INTRODUCTION

As we observe parameters of equation (4), $\rho$ and $V$ are not controllable parameters because those depends on the nature and environment, $A$ is constant and depend on the Turbine Design, only $C_p$ is controllable parameter so we can write that mechanical power is function of Power coefficient $P_{mech}(C_p)$, now from the equation (4) we can see that power coefficient is function of Tip Speed Ratio and Pitch Angle, $C_p(\lambda, \beta)$ and in our case pitch angle is constant because we have stall regulation control means the blades of wind turbine are not movable. So we can correct ourselves that power coefficient is function of tip speed ratio $C_p(\lambda)$. So we can write that $P_{mech}(\lambda)$

Now as we know that:

$$\lambda = \frac{\alpha R}{V}$$

In equation (22) $R$ is constant, $V$ is not controllable as mentioned earlier, the remaining parameter is only $\omega$...
which can be controlled it means \( \lambda(\omega) \), consequently we can say that the mechanical power is the function of generator speed \( P_{\text{mech}}(\omega) \). Now for understanding the roots of the problem we will plot Mechanical Power Versus Generator Speed \( P_{\text{mech}}(\omega) \) as follows:

From (22) we find that:

\[
\omega = \frac{V_{\omega}}{R}
\]  

(23)

So now if we give \( \lambda = 1:0.1:15 \) and plot the mechanical power versus speed as illustrated in Fig.7 it has a nonlinear relationship means up to particular speed the power is increasing above that speed the power will decrease again so that is why it is necessary in wind turbine to track that maximum power point to get maximum output power.

![Fig. 7: Mechanical Power Versus generator Speed](image)

VII. PROPOSE METHOD FOR THE SOLUTION

And for the solution of above problem we will act as follows:

In the equation (5) \( C_p \) is the function of \( \lambda \) (Tip Speed Ratio) and \( \beta \) (Pitch angle of blades of the wind turbine) as shown in Fig.8 and as per Bet’z Law 59.3% of the total wind can be extracted as mechanical power [17] so it means maximum value of \( C_{p} = 0.593 \). But practically it is not possible because of the losses. Practically \( C_p \) can be derived from equation (5) and it is illustrated in Fig.8

![Fig. 8: Power Coefficient versus Tip Speed Ratio](image)

According to the equation (5) we put different values of \( \beta \) as shown in Fig.8 and we give the \( \lambda = 1:0.1:20 \) from 1 up to 20 with the steps of 0.1 and we get the maximum power coefficient value at \( \beta = 0 \), \( C_{p} = 0.48 \) as shown in Fig.8

Now we consider \( \beta = 0 \) at the equation (6) and we get:

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda} - 0.035
\]

(24)

And here we will equate \( \frac{1}{\lambda_i} = L_i \) to become easy for the calculation and now we will find the value of \( L_i \) which is constant at the maximum power point where the \( C_p = 0.48 \) as illustrated in the following Fig.9

![Fig. 9: \( C_p \) Versus \( L_i \)](image)

As it is seen in the above Fig.9, \( C_p = 0.48 \) and \( L_i = 0.0885 \) which is a constant value and now we will be calculating optimal generator speed using the \( L_i = 0.0885 \) Value.

From the equation (24) we can find \( \lambda \) as:

\[
\lambda_{\text{opt}} = \frac{1}{L_i + 0.035}
\]

(25)

As we know that the wind turbine tip speed ratio is:

\[
\lambda = \frac{\omega R}{V}
\]

(26)

From (23) we find that:

\[
\omega = \frac{V_{\omega}}{R}
\]

(27)

Now in the equation (27) we put the optimal value of \( \lambda \) from (25) and it will give us the optimal speed of the generator as follows:

\[
\omega_{\text{opt}} = \frac{V_{\omega}}{(L_i + 0.035)R}
\]

(28)

Here \( \omega_{\text{opt}} \) generator speed in (rad/sec), \( R \) is the radius of rotor in (meters), and \( V_{\omega} \) is the wind speed in (m/sec).

As we see from the above equation (28) the optimal value of the generator is the function of wind speed means that according to the wind speed the optimal speed of the generator will be varying and will give us the proportional control signal for getting the maximum power.

VIII. PARAMETERS

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out Power</td>
<td>( P_{\text{mech}} )</td>
<td>16228</td>
<td>Watts</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>( V_{\text{cut-in}} )</td>
<td>3.5</td>
<td>m/sec</td>
</tr>
<tr>
<td>Rated Wind speed</td>
<td>( V_{\text{rated}} )</td>
<td>12.5</td>
<td>m/sec</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>( \beta )</td>
<td>0°</td>
<td>degree</td>
</tr>
<tr>
<td>Turbine Rotor Radius</td>
<td>( R )</td>
<td>2.8</td>
<td>M</td>
</tr>
<tr>
<td>Power Coefficient</td>
<td>( C_p )</td>
<td>4.8</td>
<td>Ratio</td>
</tr>
<tr>
<td>( L_i )</td>
<td>( L_i )</td>
<td>0.0885</td>
<td>Ratio</td>
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</table>

Table 1: Wind Turbine Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>( P_e )</td>
<td>16228</td>
<td>Watts</td>
</tr>
<tr>
<td>Rated DC Voltage</td>
<td>( V_{0,\text{rated}} )</td>
<td>400</td>
<td>Volts</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>( r )</td>
<td>0.087</td>
<td>ohms</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>( L_p, L_q )</td>
<td>2.49</td>
<td>mH</td>
</tr>
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Table 2: Generator Parameters

<table>
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<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux induced by magnets</td>
<td>$\lambda_m$</td>
<td>0.442</td>
<td>Wb</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>J</td>
<td>0.296</td>
<td>Kg.m²</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>P</td>
<td>5</td>
<td>-</td>
</tr>
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</table>

Table 3: Boost Converter Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Load side capacitor</td>
<td>$C_0$</td>
<td>20</td>
<td>mF</td>
</tr>
<tr>
<td>Inductor</td>
<td>$L$</td>
<td>0.013</td>
<td>mH</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_{dc}$</td>
<td>50*e-7</td>
<td>kHz</td>
</tr>
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</table>

IX. SIMULATIONS

Fig. 10: Complete Simulation of Wind Turbine Generation System

Fig. 11: Simulation of PMSG & Rectifier
X. RESULTS

Fig. 12: Simulation Boost Converter & MPPT (Maximum Power Point Tracking)

Fig. 13: Wind Speed (Vw) VS Time (sec)

Fig. 14: Optimal and Attained Speed of Generator (ωopt & ωa)

Fig. 15: Desired & Attained Power Coefficients

Fig. 16: Mechanical Power (Pmch) VS Time

Fig. 17: Line Current (Iab)

Fig. 18: Input DC Voltage of the Boost Converter (Vdc)

Fig. 19: Output DC Voltage of the Boost Converter (Vo)

XI. CONCLUSION

In this Research Paper I have developed MPPT through calculation of optimal generator speed and the optimal value of the generator is used as control signal for controlling the speed of the generator.

For fulfilling this proposed MPPT control scheme I have used MatLab/SIMULINK.

The Wind Turbine Generation Equipment in this paper were Wind Turbine, Permanent Magnet Synchronous Generator, 3 phase Bridge Rectifier and Boost Converter.
As it seem from the Result this MPPT control scheme is working quite impressive and can track the maximum power point efficiently so this MPPT control scheme can be applied to any installed wind turbine in real time.

REFERENCE


