Abstract

Power Point trackers for increased efficiency in the power production of wind turbines are investigated. The power point trackers are to be used for large scale and small-scale systems. Two basic methods for tracking are presented. The first method is rudimentary load adjusting in sample steps. The second method requires previous knowledge of the parameters of the wind turbine to provide an optimal look-up table. The loading of the wind turbines is determined by these power point trackers and will be implemented on a practical system by controlling the rectification from the generator. Computer simulations are performed on the proposed methods and the results are presented in this paper. An analogue model was also created and the preliminary results are presented.

I. INTRODUCTION

Renewable energy resources are fast becoming very popular in a world where demands for more power and sustainable development are increasing dramatically. Wind energy is gaining momentum in this field of “clean” energy. The gap between costs of generating power through fossil fuels and generating power through wind is getting smaller as the wind turbine technology gets more affordable. Factors like carbon taxes also improve the competitiveness of renewable technologies. Europe has been a leader in wind energy as countries like Denmark generate a large proportion of their nation’s electricity through wind farms.

In South Africa wind energy is being investigated for small stand-alone systems in remote areas as an alternative to the dominated field of solar panels. This is due to the huge losses of panels as a result of theft [1]. Wind turbines are not attractive to thieves due to their complexity. Large-scale wind turbines are also being investigated as a generation medium for the nation’s electricity grid [2].

In order for wind energy to be an attractive alternative, the wind turbines need to be very efficient in harvesting energy. The wind turbine can only provide a maximum power for a particular wind speed and an attempt to try and acquire more power by decreasing or increasing the load on the generator, will result in an inefficient transfer of power from the wind.

The high cost of power production in wind turbines has lead to investigations into more efficient systems for large-scale projects in the region of 100’s of kW. Smaller wind turbines used for power to remote locations, need efficient systems to keep their storage units charged, even under periods of little wind.

Power point trackers are algorithms that control the loading on a particular source so that the optimal loading can be obtained. This can be achieved under various load conditions by using energy storage for excess or shortage of power.

The large wind turbine system which range from the 100’s of kilowatts upward, use pitch control of their blades to extract the maximum available power from the wind. The largest wind turbine systems incorporate a regenerative slip control system on their induction machines in conjunction with the pitch control for a more efficient system. The additional price of these methods on small-scale systems far outweighs the cost savings and so a cheap alternative is required.

There are two power point trackers proposed in this paper. The first one is very rudimentary and is based on the power point trackers used in photovoltaic arrays (solar panels) and has been found to work very well with them. As will be shown later, this is not necessarily the best method to use with wind generation. The second method requires that the wind turbine characteristics are known prior to implementation. The initial method requires an anemometer to measure the wind speed striking the rotor. This is feasible with larger scale turbines since the cost of the additional anemometer is small as compared to the overall system. An alternative and improvement on this system was created resulting in the removal of the anemometer.

II. SYSTEM DESCRIPTION

The system that is investigated for these power point tracking methods is shown in figure 1. It must be remembered that these power point tracking methods are also intended to be used on large-scale, grid connected wind turbines, with the only difference being that there is no storage medium needed in such a system.

![Fig. 1: System Outlay](image)

The entire system of a small-scale wind turbine plant (typically below 10 kW) under investigation comprises of the following sub-systems:

- A generation unit consisting of a wind turbine
• An active rectifier connected between the wind turbine and a DC bus
• A storage unit connected to the DC bus (note, a large scale system connected to a grid does not necessarily need storage)
• An inverter to provide either a DC output at a desired level, or an AC output.

The loading on the generator in a system utilizing a power point tracker is determined by the power point tracker and controlled by the active rectifier connecting the generator to the DC bus.

The generator to be used in these systems is a 3-phase, axial flux, permanent magnet, synchronous machine. This machine was developed specifically for this project. The synchronous system insures that the electrical frequency of the voltage on the output is in proportion to the rotor speed. This is important for the some of the power point tracking methods as will be seen later in this paper.

III. POWER POINT TRACKING

In order for a wind turbine to harvest the maximum amount of energy available from the wind at any given instant, the load applied to the generator needs to be correct for that available energy. This ensures that the maximum power transfer from the wind’s energy to electrical energy is realized. If the load is too large or too small for a particular wind speed, the rotor speed deviates from optimal point and the output power is less. This can be seen in figure 5.

A method to determine the optimal loading on the generator at any specific time is needed. Two main proposals are explored with each method having a slight extension in their methodology. The two main methods are referred to as Step Control and Equation Control for the purposes of this paper, with Constant Step Control and Variable Step Control referring to the two variations of Step Control and Anemometer Equation Control and Calculated Equation Control referring to the two variations of Equation Control.

A. Step Control

A-1) Constant Step Control

The first method involves a constant revision of the power produced by the wind turbine. By changing the duty-cycle of a converter, the load impedance is effectively being increased or decreased in increments during each sampling interval (steps). The output power produced at a time \( t \), is compared with the output power produced at one sample time later, \( t + t_s \). If the latter power measured is larger than the original power value, then the load value is changing in the correct direction and the load values are left to change in that direction. If the latter power value is smaller than the previously measured output power, then the load impedance’s change is in the incorrect direction and so the control system changes the load from an increasing value to a decreasing value or visa versa. The dynamics of the generator is such that the system needs time to settle before the new increment or decrement in the load can be made. The inability of the system to settle and the constant variation in the wind speeds, leads to the power point tracker lagging.

A-2) Variable Step Control

Another variation on the above method was investigated to try and to allow the tracker to respond faster. If the rate of change in the output power was large, then the increments in the load change were set to be larger. And as the rate of change of the output power became smaller, which meant that the output power was close to rated power; the increments were set to be smaller. This was achieved by adjusting the increments to be in proportion to the power difference over one sample period.

B. Equation Control

B-1) Anemometer Equation Control

The second method makes use of a look-up table or a predetermined equation, which explains the relationship between the wind speed and the optimal load required for that particular wind speed. The current wind speed is measured via an anemometer and the load value required for optimal efficiency is calculated.

Once the optimal loading for various wind speeds is determined, an equation describing the relationship is deduced. Figure 2 below is an example of the optimal loading against the wind speeds.

The '*' points are points of the maximum available power at different wind speeds, and the remaining trace is an equation that describes the optimal power at those different wind speeds closest, i.e. a fitted equation for the '*' trace.

When the wind speed is obtained from the anemometer, the optimal load corresponding to that wind speed is calculated from the fitted equation (a look-up table can also be used) and
the load can be adjusted for maximum power transfer. Figure 3 shows how the system follows a triangular wind profile. It can be seen from the repetitive nature of the output power trace that there is no lagging and that the resultant output power has the same results when the wind profile repeats itself.

**B-2) Calculated Equation Control**

An improvement on the method needing an anemometer is to calculate the wind speeds striking the rotor by only using the electrical parameters available from the generator.

The profiles of the power produced by the wind turbine blades verses the rotor speed for different wind speeds, as shown in figure 5, are available from the manufacturer of the blades. The data points are unique for each individual wind speed. Because the electrical frequency, which is proportional to the rotor speed, and power produced by the wind turbine can be measured, the wind speed that is striking the blades at the specific moment can be calculated. This is done by using a few characteristic profiles for different wind speeds and superpositioning the wind speed at that specific point. Once the wind speed is known, the equation method of calculating the optimal load can be used. This method in effect removes the need for an anemometer.

**IV. SIMULATIONS**

**A. Simulation Setup**

Figure 4 below is a complete equivalent control block diagram of a wind turbine, from the wind speed that strikes the blades, to the power supplied to the load.

The wind turbine can be split into two halves, the rotor and the generator. For the objective of this computer simulation, the load was modeled as a variable resistance. The loading in a practical system is controlled by an active rectifier.

**A-1) Rotor**

The rotor is influenced by wind striking it and the opposing torque from the generator. The generator exerts an opposing torque from the induced current in the rotor windings. The difference between the torque produced from the rotor and the counter torque exerted from the generator, will lead to acceleration of the rotor until the torques balance each other out at a certain rotor speed. The acceleration/ deceleration rate is determined by the amount of inertia the rotor (and generator) has.

**A-2) Generator**

The voltage induced in the generator is directly proportional to the speed of the rotor. The two internal voltage drops shown in the system diagram are due to the winding impedances: the coil’s resistance and inductance.

The characteristic torque curves for individual wind speeds of the wind turbine are determined by the blade dynamics of the rotor. The power to torque relationship is expressed by the following equation.

\[ P_r = T \times w_r \]  

(1)

The torque is curve is multiplied by the rotor speed for that specific wind speed to get the power produced verses the rotor speed for various wind speeds.

Note that the apex of the torque curve for various wind speeds in figure 5, doesn’t translate to the maximum power available. The torque that corresponds to the maximum power available has been marked with a dot for each wind speed.

The torque curves versus rotor speeds for different wind speeds is used in the simulation to characterize the blades profile. The simulator is fed various wind speeds and the appropriate torque curve is selected. If the wind speed inputted has not got a specific torque curve assigned to it, a torque value is calculated using superpositioning of the two nearest torque curves for that specific rotor speed.

Power generated in the system is not only directly from the wind, but also from acceleration or deceleration of the rotor. This happens when there is a change in the rotation energy \( W_r \).

This power contribution \( P_{ad} \), is expressed in the following equations.

\[ W_r = \frac{J \times w_r^2}{2} \]  

\[ P_{ad} = \frac{dW_r}{dt} \]

\[ = \frac{\Delta W_r}{\Delta t} = \frac{J(w_r(t))^2 - w_r(t - \Delta t)^2}{2\Delta t} \]  

(3)

\( J \) is the inertia of the rotor and \( \Delta t \) is the interval over which the sample is taken [4].

**B. Simulation Results**

The three different power point tracking methods were each simulated with the same inputted wind to the system. The wind profile was randomly created previous to the simulations and used for each simulation. From figure 6 below, it can be seen...
that the equation method of tracking is superior to the other step methods.

The total energy captured for the same wind profile using the different tracking methods over 200 seconds is shown in Table 1 below.

Table 1: Average Output Power

<table>
<thead>
<tr>
<th>Power Point Tracker Method Used</th>
<th>Average Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Step Control</td>
<td>324.1</td>
</tr>
<tr>
<td>Variable Step Control</td>
<td>322.9</td>
</tr>
<tr>
<td>Equation Control</td>
<td>333.2</td>
</tr>
<tr>
<td>Calculated Wind Control</td>
<td>329.2</td>
</tr>
</tbody>
</table>

V. ANALOGUE MODEL

The algorithms proposed and computer simulated were then tested on an analogue model. This system is modeled around the actual wind turbine and the process from the different wind speeds striking the blades to the DC current used to charge a lead acid battery is simulated. Fig. 7 below shows the setup used.

VII. ANALOGUE MODEL RESULTS

The measurement system used in the active rectifier proved to be very insensitive and was the cause of many difficulties. The constant drifting of the measurement meant that the correct power delivered to the load was often incorrectly measured.

A variation on the step control methods was implemented in the active rectifier. This involved the altering of the load at a constant rate. This method was used to eliminate the “ringing” induced on the output as a result of the step changes in the other methods. Incorrect measurements meant that the controller often calculated the peak in the received power where there wasn’t one. A power allowance was incorporated into the program, which cushioned the measurement of the output power. This alteration allows for a slight measurement error, but also makes the system slightly less efficient.

Figure 8 below shows the logged output power of the active rectifier, which is measured over the load. A constant wind speed was used for this simulation and the power was logged at 0.4s intervals. The ideal waveform would be a constant maximum output power. The rising and falling slopes are a result of the alteration of the method described above.

VI. ANALOGUE MODEL RESULTS

The output power points corresponding to the respective frequency of the received waveforms, from the simulation above, are plotted in figure 9. The points that were logged can be shown to resemble the peak of the power profile for that particular wind speed as can be seen in traces figure 5. From this it can be seen that the most of the electrical power transferred to the load, is the maximum power available.
The average power that the above test rendered was 219.22 W. Another test was run to determine the maximum power available at the output under the same conditions. This test showed that the maximum available power was 223.15W. These results show that the above tracker system has an efficiency of 98.2%.

A triangular inputted wind speed varying from 8m/s to 14m/s was also tested. The two output power traces of the two simulated methods are portrayed in figure 11. It can be seen once again that the calculated equation method is superior to the step method. The need for fine-tuning in the calculated equation method is evident once again at low wind speeds.

VII. CONCLUSION
The variable step method used in the computer simulations was not superior to the constant step method as was hoped. The method of predetermining an optimal loading equation was the best method and had an average energy capture that was larger than the other two methods. Because the equation method deals directly with the wind speed striking the blades and not on feedback from the power produced, there is no lagging of the system, whereas the step methods are never able to reach their desired quiescent values in time. The sudden step also leads rise to a step response type of output from the system and this has to be left to settle before the next increment can be made. This takes time and also leads to the systems lagging. The output power using the equation method also seems to be less chaotic.

These methods are acceptable in principal but the effects of acceleration and deceleration during wind speed changes, which provide extra power, need to be taken into calculation consideration. Inertia of the blades also needs to be investigated in more detail.

The analogue tests done confirm that the Calculated Equation Control method is the superior method in Maximum Power Point Tracking applications. Further tests must be done to fine tune the programmed algorithm.

The inverter can now be used to drive the actual wind turbines generator. This eliminates the need to rely on the wind in order to perform different tests. The inverter is programmed with the exact power profiles of the blades that are to be used in the field and so the results obtained in testing can be expected with a high level of accuracy in the practical system. The inverter will be used to drive a synchronous machine that in turn will drive the generator. The power delivered to the generator will be measured either via an electrical or mechanical transducer. This feedback result is needed for the operation of the blade characteristics.

REFERENCES
Gary D. Moor attended the University of Stellenbosch where he obtained his B.Eng degree in 2001. He is currently completing his M.Sc Eng at the same institution. He is an employee of Telkom (Ltd.) in the CoE program and his fields of interest include renewable energy and network integration utilizing power electronics.