6-2013

Control System for a Doubly Fed Induction Generator

Nathan Haines
Union College - Schenectady, NY

Running Title: DFIG Control System

Control System for a Doubly Fed Induction Generator

By

Nathan Haines

* * * * * * * * *

Submitted in partial fulfillment

of the requirements for

Honors in the Department of Electrical Engineering

UNION COLLEGE

June, 2013

ABSTRACT

HAINES, NATHAN The control system for a Doubly Fed Induction Generator: A study in the feasibility of small scale wind power generation.
Department of Electrical Engineering, June 2013.

ADVISOR: Professor Robert Smith

Doubly Fed Induction Generators (DFIGs) are typically used in large scale (three to five Megawatt) wind turbines because they can be operated over a wide range of wind speeds, have flexible control systems, power electronics need only pass about 30% of the generator power, and the windmill experiences fewer mechanical stresses. This project is to construct the control system for a DFIG. This control system will be used to test the feasibility of using a DFIG on a small-scale wind turbine. Testing confirms that the DFIG delivers power over a wider range of simulated wind speed than a standard induction generator does and delivers an average of 54% more power than a standard induction generator.

Forward

The demand for alternative energy has grown due to its potential to slow global warming and reduce dependency on foreign fossil fuels. The use of wind power is a viable way to produce large amounts of clean energy. Doubly Fed Induction Generators (DFIGs) are used in large-scale wind turbines. The overall goal of this project is to construct a working control system for a Doubly Fed Induction Generator. This will be tested to determine if Doubly Fed Induction Generators are viable for small-scale power generation. This project is broken into two parts; part of this project is making the hardware prototype of an inverter while the other part of this project is programming the inverter.

When constructing the inverter it is important that the switches in the inverters can be fired at a fast enough rate so that they can produce a sine wave that is compatible with the grid. It is also important that the transistors in the inverter are able to handle the amounts of power, current, and voltage that is going to pass through them. For the inverter to work properly, the inverter must have a control scheme that is working correctly. The control scheme must be able to change the frequency of the sine wave that is generated by the inverter based on the speed of the rotor. The control system should also be able to adjust its output shush that the DFIG provides the maximum possible power to the grid, using a type of hill-climbing technique called perturb and observe.

Through testing it is proven that the DFIG delivers more power over a wider range of rotor speeds when compared to a standard induction motor. It is also shown that the DFIG with maximum power point tracking is able to deliver more power than the DFIG without maximum power point tracking. As the DFIG is able to deliver power over a wider range of wind speeds it is viable to use a DFIG in a small scale wind turbine.

Table of Contents

List of Figures

List of Tables

1. Introduction

Doubly Fed Induction Generators are commonly used in large-scale wind turbines, typically three to five megawatts [Fletcher]. They have the advantage of being able to operate over a wide range of wind speeds; they have the ability to track the maximum power point; they have flexible control systems; the power electronics need only pass about 30% of the generator power which decreases losses and costs [Fletcher]; and the windmill experiences fewer mechanical stresses. However, these qualities have not been taken advantage of in small-scale wind turbines to a great extent. This project will explore the feasibility of Doubly Fed Induction Generators used in small-scale wind turbines.

The objective of this project is to design, build, and test the control system of a Doubly Fed Induction Generator. This project will be a success if it the generator is able to efficiently react to changing wind speeds. To make that happen, the control system will need to be able to monitor and react to changes in rotor speed. It will also need to produce output currents and voltages that do not add excessive ripple to the grid.

The remainder of this paper is oriented as follows. Section 2 contains the ethical, environmental, political, health, and economic issues of this project. Section 3 will evaluate the design requirements for this project. Section 4 will analyze the design alternatives that are available. Finally, Section 5 will propose the preliminary design of the project.

2. Background

Since Doubly Fed Induction Generators are commonly used in wind turbines, the consequences of installing wind turbines need to be considered. The increase in wind energy installations could have long lasting positive effects on society and the world. However, there are ethical, political, environmental, health and economic impacts that increased wind power could have. All of these issues need to be considered and evaluated before projects like this one are considered.

2.1 Ethics

Ethical issues that have to do with wind power are the noise pollution that wind turbines cause, the death of birds and bats due to the turbines and the aesthetic degradation of the landscape. These issues have to be balanced with the potential that wind turbines have to decrease the amount of greenhouse gasses that are produced.

Wind turbines certainly can be destructive if they are placed in incorrect places. However, “adverse impacts that could be caused by wind power can be avoided or greatly minimized through thoughtful project siting decisions.”[Brown] Additionally, it is argued that the destructive properties that wind turbines have are minimal compared to the impacts that other forms of power generation have. Wind turbines do kill some birds and bats, but that is minimal compared to the impact that global warming will have on these animals. Whole populations of birds and bats and other animals could go extinct if global warming is not checked. Wind turbines may cause noise pollution but this noise pollution only occurs in the immediate vicinity of the wind turbines. Greenhouse gasses on the other hand have far reaching consequences. For example, “Climate change-caused harms that are already being experienced by some people are of many types including,

but not limited to, death, disease, ecological harm, flood and droughts, rising seas, more intense storms, and increased heat waves."[Brown] Thus, it seems that the benefits that wind turbines have are ethically more significant, as long as they are placed at appropriate sites, then the problems that they cause.

2.2 Politics

There are a variety of political issues surrounding wind turbines. One of the most pressing issues that face wind energy in the US is the fluctuating energy policy. This policy has fluctuated due to petitioning by groups in the energy industry that are hurt by wind power. One of these groups is a group of East Coast utility companies. This group, called the "Coalition for Fair Transmission Policy" fears that the prime conditions in the Great Plains will make the region's wind power too cheap for its members to compete with, unless developers there are made to pay the costs of moving wind power eastward."[Behr] Another of these groups that is worried is a group of natural gas producers in Texas. "They are demanding that the state's wind developers share the costs of backup natural gas generators that must pick up the slack when the wind doesn't blow"[Behr]. This group wants penalties on wind generators when they can't deliver scheduled wind energy. Finally there is a group of senators that is opposing federal clean energy grants to wind developers who are buying parts from outside of the country. All of these political issues have caused uncertainty within the alternative energy industry in the US. This has caused the development of the wind power industry to be slowed.

2.3 Environment

Wind power has enormous potential to reduce greenhouse gasses. This would help with the monumental problem of global warming. However, the construction of

wind turbines can have adverse environmental effects. Some of these effects are the construction of access roads, the installation of transmission lines, the construction of power substations, and excavation for turbine foundations. Despite these adverse environmental effects the alternative needs to be considered. With the energy demand growing, energy production needs to grow with it. If wind turbines don't fill this void, it will be filled with new fossil fuel, natural gas, or nuclear power plants. These power plants have just as many, if not more, environmental impacts that are even more permanent. They will also increase the amount of green house gasses that are produced. Thus, wind turbines are less intrusive then other conventional forms of power generation. [The Wind Power Problem]

2.4 Health

There have recently been some questions raised about the health risks of living close to a wind farm. There have been reports of something called wind-turbine syndrome. The symptoms of this are sleep disturbance, headaches and concentration problems. These symptoms occur in people who are living close to wind turbines. It is hypothesized that the sound pollution and changes in pressure caused by the turbine blades make it difficult to sleep. To counteract these effects engineers are working on ways to reduce the amount of noise that wind turbines make. It is also suggested that there be a 1.2-2 mile buffer zone for residential areas around large wind farms. This should protect people from any ill effects. [HowStuffWorks]

2.5 Economy

Wind farms have a positive effect on the economy. Wind farms bring hundreds of jobs during the construction of wind turbines. They also bring in permanent

operations and maintenance jobs. The taxes are also collected from the wind farms that flow into the local community. The companies that own the farms also pay landowners to put the turbines on their land. Many of the areas that turbines are being put in are rural areas so this has a large effect on these rural communities. The construction of wind turbines also “creates the demand for turbines and turbine components, which stimulates the manufacturing sector”[Wind-energy-economy].

3. Design Requirements

One of the most important aspects of a Doubly Fed Induction Generator is that it can operate over a large range of wind speeds. In order for this project to be a success, the control system must be able to extract power from the generator at sub-synchronous and super-synchronous speeds. Theoretically a DFIG can operate at plus or minus 50% of its synchronous speed. In practice they are only used when they are plus or minus 30% of their synchronous speed. [Hu, 14] Thus this project will be successful if the DFIG can deliver usable power to the gird over plus or minus 30% of synchronous speed.

The inverter uses an I/O board to measure the voltage at the stator windings so that the power that is delivered to the grid can be calculated. In order to calculate the power accurately, the RMS voltage needs to be calculated. To do this the I/O board needs to take samples at a set time interval so a full period of samples can be taken. The I/O board is also used to generate the currents that are applied to the rotor windings. The I/O board must be able to generate a Pulse Width Modulation signal at a frequency that meets industry standards. This is necessary to generate a sine wave that will be compatible with the gird. For this project the grid is simulated so that much smaller voltages and currents are used. This is done to make the testing of this project safer.

The control system must also be able to change the frequency and magnitude of the currents it is applying on the rotor from Rotor Side Converter. This is necessary to be able to modify the rate at which the rotor's magnetic field is rotating so that the Doubly Fed Induction Generator is able to operate at a range of wind speeds.

4. Design Alternatives

Two alternatives to using a Doubly Fed Induction Generator in small-scale wind power generation include using either a synchronous generator or a DC generator. A synchronous generator has the ability to connect to the grid to sell power back to the power company. A DC generator could be used to charge a bank of batteries. These batteries could be used to power a house or small business, or they could be used as energy storage before being converted into AC.

There are also alternatives to using a hill climbing technique to track the maximum power point. One alternative is to have a pre-determined maximum power curve based on currents and voltages specific to the generator. Another technique is to monitor the wind speed to estimate the power that the generator can output and make adjustments based on the power error [Thiringer].

4.1 Synchronous Generator

In a synchronous generator a constant DC voltage is applied to the rotor windings and the grid is connected to the stator. The resulting rotor current causes the rotor to have a constant magnetic field. The AC voltage applied to the stator also generates a rotating magnetic field. The magnetic field of the rotor and stator are always rotating in the same direction and at the same speed. The rotor field cuts through the stator windings, and induces a stator voltage if an attempt is made by the prime mover (in the case of a wind turbine the prime mover is the wind) to spin the rotor faster then the rotating stator magnetic field.

4.2 DC Generator

In DC generators the stator has a permanent magnetic field that is either induced by a DC current in the stator windings, or created by permanent magnets mounted on the stator. The rotor has windings that run along its length. Every 180 degrees, when the windings are directly between the north and south poles, the direction of the current switches by using a commutator. As the rotor spins, the magnetic field induces current onto the rotor windings. The direction of the current switches so that the current that is induced is always positive. The progression of how the current direction changes can be seen in Figure 1 below.

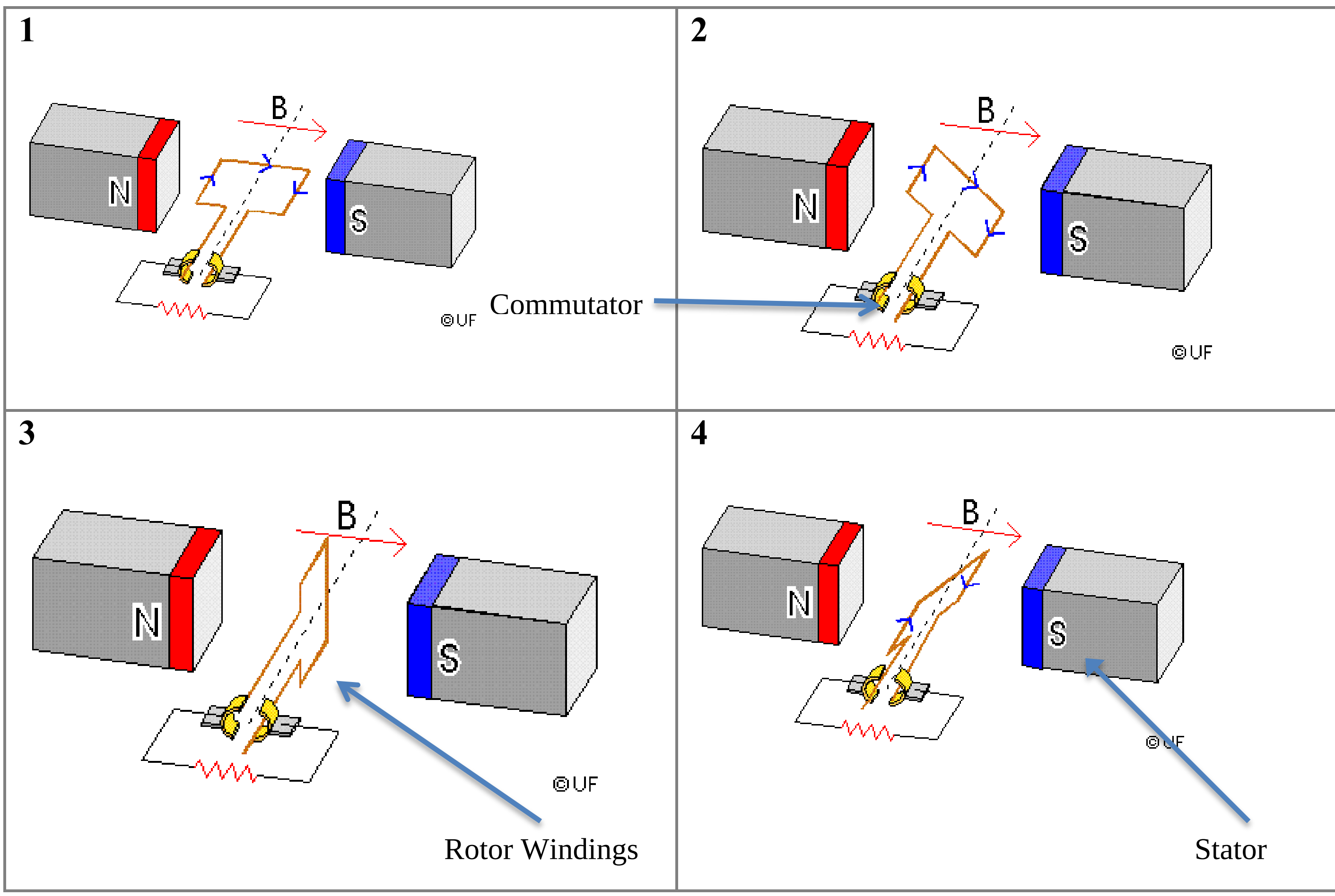

Figure 1: Shows the direction of the magnetic field and current at different points of rotation in a DC Generator.

4.3 Generator Characteristics Power Tracking

In this technique there is a predefined power ratio that is used to track the maximum output power of the generator. "The power is controlled in order to follow a pre-defined turbine power speed characteristic to track the maximum power point. The actual electrical output power from the generator terminals added to the total power losses (mechanical and electrical) is compared with the reference power from the wind turbine characteristics." [Fletcher, 268] However this method is not ideal for mass sale. This is because every generator has slightly different characteristics. This means that every generator would need the control system to be custom made for each generator.

4.4 Wind Estimation Power Tracking

Using the wind to estimate the power that the turbine will produce is very difficult to do. Since there is a time delay between when the gusts of wind arrive at the turbine blades (due to something called the inertia effect) and when the power is produced at the generator it is difficult to predict the output power. The placement of the anemometer is also difficult because it is either in front of or behind the turbine blades [Thiringer].

5. Final Design

5.1 DFIG overview

Doubly Fed Induction Generators have some similar basic concepts as standard induction machines. Some of the concepts of a standard induction machine will be explained to highlight a DFIG's unique properties and to help explain how a DFIG works.

A standard induction machine's stator is connected directly to the grid. This creates a magnetic field in the stator. The magnetic field in the stator rotates at a constant rate because the grid has a constant frequency. This stator magnetic field induces a magnetic field in the rotor's shorted bars (or shorted windings in the case of a wound rotor induction machine).

The rotor magnetic field has to rotate at the same frequency as the stator magnetic field. However, the angle between the stator and rotor magnetic fields changes with the slip. Slip is defined as follows:

$$Slip = s = \frac{nsync - nm}{nsync}$$

Where: $nsync = mechanical\ speed\ of\ the\ stator\ magnetic\ field\ in\ rpm$

& $nm = mechanical\ speed\ of\ the\ rotor\ in\ rpm$

The larger the magnitude of the slip, the larger the magnitude of the angle between the stator and rotor magnetic fields. The polarity of the slip determines if the rotor magnetic field leads or lags the stator magnetic field (if slip>0 the rotor magnetic field lags the stator; if slip<0 the rotor magnetic field leads the stator magnetic field). A diagram of the stator and rotor magnetic fields can be seen in Figure 2.

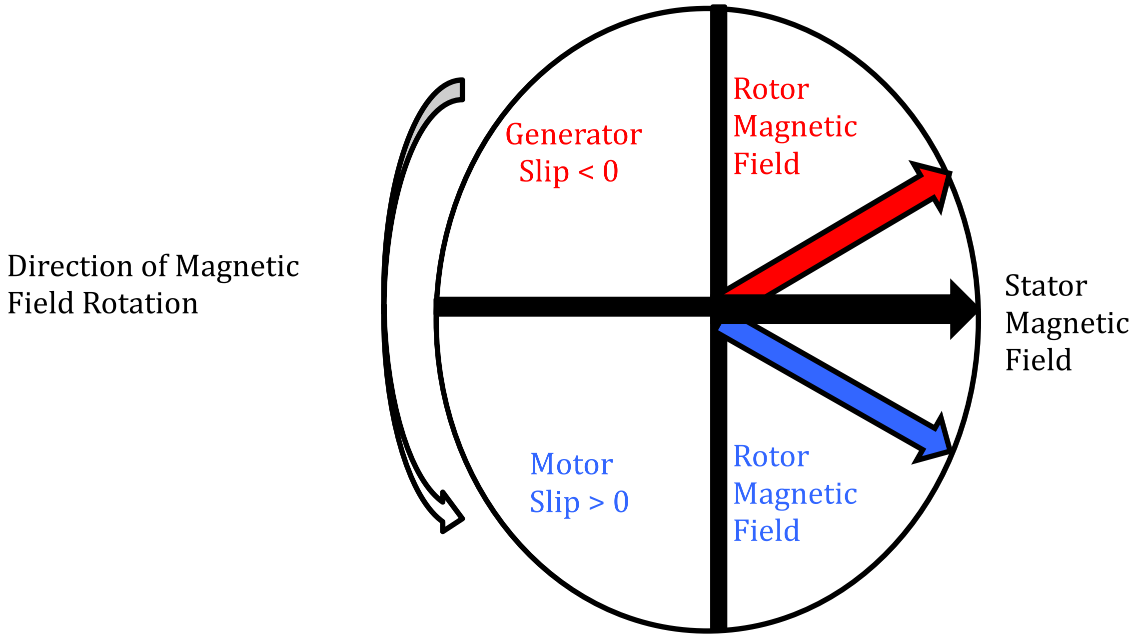

Figure 2: Shows the stator magnetic field and the location of the rotor magnetic field when there is a positive or negative slip.

One useful model of a standard induction machine is that of a rotating transformer. If it is thought of in this way, the single phase equivalent circuit can be seen in Figure 3.

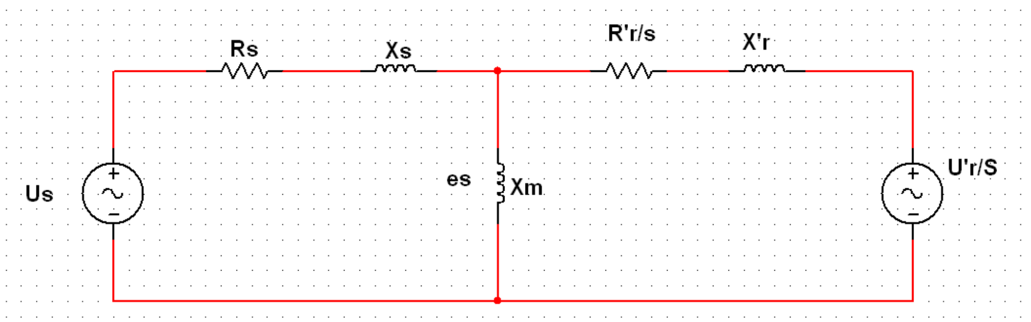

Figure 3: Single phase equivalent circuit with core losses neglected and secondary reflected onto the primary

From Figure 3 we can see that when the slip is greater than zero, mechanical power is supplied to the induction machine output shaft and its coupled load . However, when the slip is less than zero, the mechanical system becomes the power source supplying current

to the grid. Thus, when the rotor magnetic field leads the stator magnetic field, the current and therefore power are supplied to the grid and from the induction generator when the rotor magnetic field lags the stator magnetic field, power is being supplied from the grid to the induction motor.

Doubly Fed Induction Generators always have a wound rotor. The rotor windings are brought out of the DFIG through slip-rings and brushes. Voltages from the DC-AC converter are applied to the rotor windings; hence the rotor currents are externally controlled. Changing the angle of theses currents has the effect of changing the angle between the rotor and stator magnetic field. Thus, the control system can change the rotor magnetic field so that it is no longer lagging when the rotor is spinning slower than synchronous speed. In this way, the DFIG can supply power to the grid even when the rotor is spinning slower than synchronous speed.

5.2 DFIG control system

The control system of the Doubly Fed Induction Generator is made up of two parts that are connected together through DC – link capacitors: the grid side converter (GSC) and the rotor side converter (RSC). The job of the RSC is to track the speed of the rotor and apply the correct frequency to the rotor windings. The RSC also has the job of maximizing the amount of power delivered to the grid. The job of the GSC is to maintain the DC-Link at a constant average voltage. It passes power to the grid from the DC-Link if the voltage of the DC-Link gets too high and it passes power to the DC-Link from the grid if the voltage gets too low. Each of these jobs is done separately. A diagram of how the control hardware is seen in Figure 4.

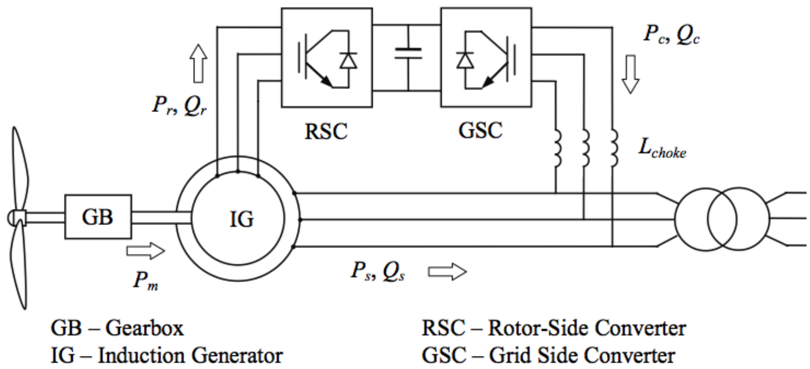

Figure 4: Control Hardware of a DFIG

At this time, the RSC has been built and programmed. Instead of being attached to the DC-Link and GSC, the RSC is attached to a DC-voltage source. The DC voltage source is taking the place of the DC-Link and GSC so the Rotor Side Converter can be tested and debugged. In the future, the DC-Link and GSC will be added to the RSC to complete the system architecture.

5.2a DC-AC converter

The RSC and the GSC are both made up of six-switch voltage inverters. Each inverter circuit is made up of three legs, one for each phase. Typically each leg is made up of two switches and two diodes as seen in Figure 5 and Figure 6. However, since the scale of this project is small, the switches don't need to be IGBTs, the switches can be MOSFETs. Also, to limit the number of outputs the control system needs, the switches are matched MOSFETs so one I/O card output can switch two MOSFETs at once.

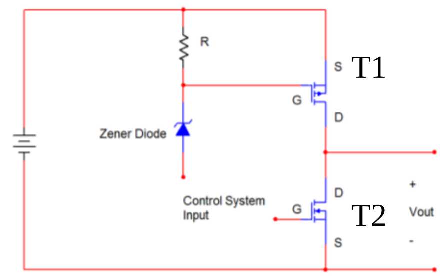

Figure 5: One leg of a six-switch inverter

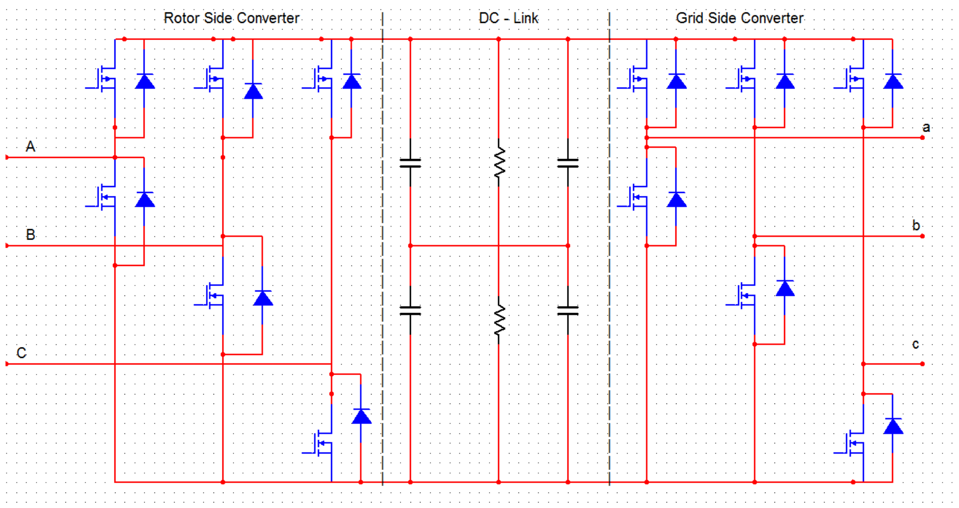

Figure 6: Circuit Diagram of RSC and GSC connected with a DC-Link

When switch T1 is on, the output voltage, V_{out} is $V_{dc,}$ the DC link voltage. When switch T2 is on, the output voltage is zero. Note that switch T1 and switch T2 can't be on at the same time. The switches are switched on and off in order to create a power frequency sine wave of the right magnitude and frequency. Switching duty cycle is determined within Simulink. Simulink evaluates different values like stator current, rotor current, stator voltage, mechanical position of the rotor and the DC-link voltage. Once these values have been evaluated an optimal reference sinusoid is determined and generated. [Fletcher]

Simulink then determines how long switch T1 and switch T2 will be on by comparing the reference sinusoid with a carrier waveform, which is a triangle wave. The carrier waveform has a switching frequency of f_{sw}, and thus a switching period of $Tsw=\frac{1}{fsw}$. Simulink and its output hardware will switch T1 on when the reference sinusoid wave is greater than the carrier waveform and will switch T2 on when the desired sine wave is less than the carrier waveform. By doing this the power frequency output over each switching period is, $V_{out,ave}=V_{DC}\frac{T1,on}{Tsw}$, and this voltage will approximate the desired sine wave [Fletcher]. This can be confirmed by filtering out the high frequencies from the output waveform. An example of the desired sine wave and carrier waveform can be seen in Figure 7. Note that f_{sw} is typically much greater than shown in the figure below, at least 100 times greater than the frequency of the desired sine wave.

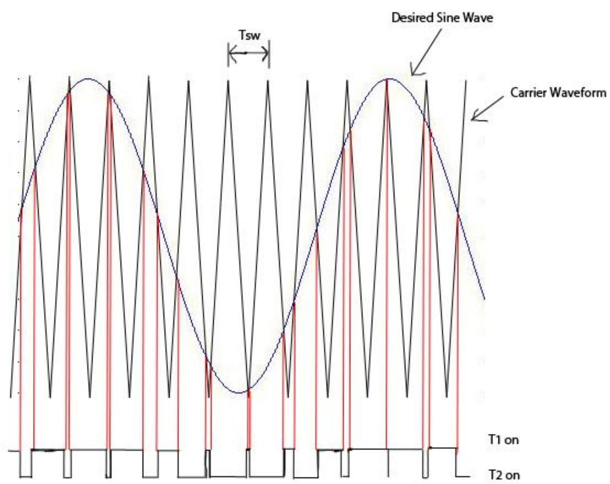

Figure 7: Desired sine wave and carrier waveform and the resulting PWM

5.2 b Programming Control System

The control system has to do three jobs. The first is to determine the frequency of the reference sine wave. According to [Fletcher] $fr = sfe$, from which the following equation can be derived:

$$Reference\ frequency(Hz) = Synchronous\ frequency(Hz) - \frac{RPMrotor}{60} \#\ pole\ pairs$$

Using this equation, the part of the Simulink program seen in Figure 8 was used to calculate the reference frequency. If a rotor voltage of the incorrect frequency is applied, the rotor magnetic field will rotate at a different speed then the stator magnetic field. This will add undesirable low frequency ripple to the grid.

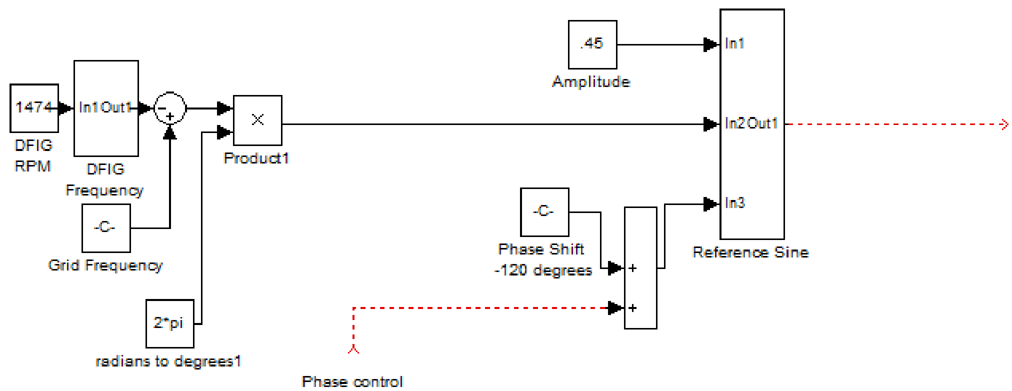

Figure 8: Reference sine frequency

The next task of the control system was to find the maximum power point for a given rotor speed. Since power delivered to the load is maximized when the angle between the stator and rotor magnetic fields is leading by 90°, the control system must try and achieve this angle. This angle can be achieved if the applied rotor currents lead the stator currents by 90°. This can be done quickly if the control system has access to the rotor position. However, since the rotor position is not yet accessible, another technique is used.

The maximum power point is achieved by using a hill-climbing technique. If increasing the phase shift of the desired sine wave increases the power delivered to the load, the phase shift is increased again. If increasing the phase shift decreases the power

delivered to the load, the phase shift is decreased. Similar logic is used for decreasing the phase shift. This part of the Simulink program is seen in Figure 9.

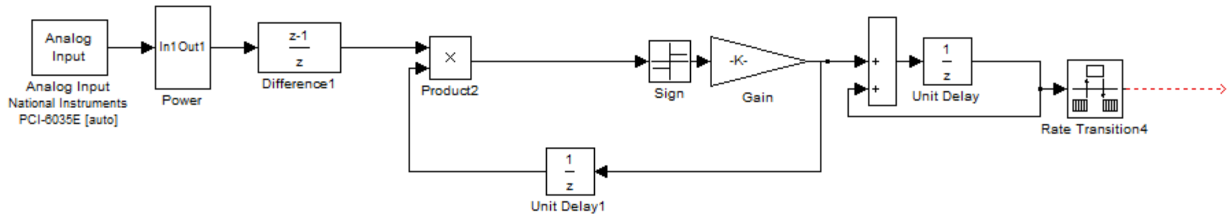

Figure 9: Maximum power point tracker by using phase angle control and a hill climbing technique.

The final job of the control system is to convert the sine wave into PWM as discussed in section 5.2a. The Simulink program for this part is seen in Figure10.

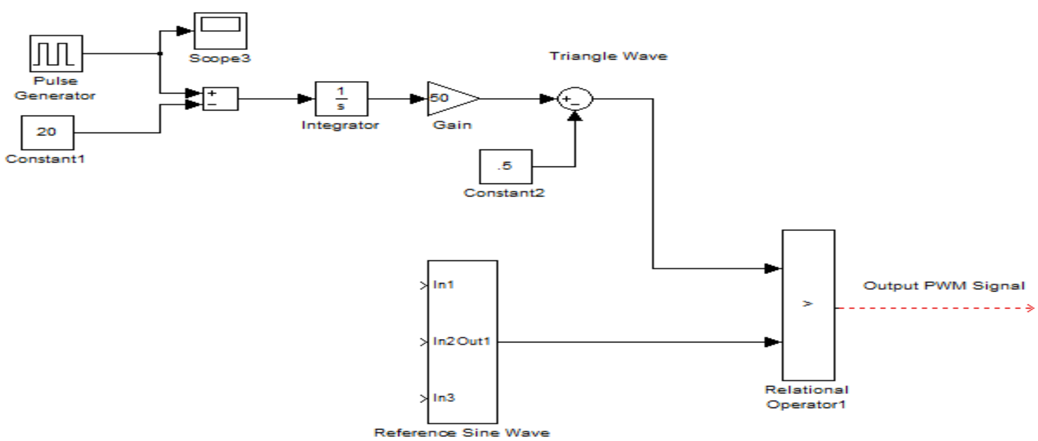

Figure 10: Compares a sine wave to a carrier to generate a PWM signal

The entire Simulink program can be seen in the Appendix

6. Performance Estimates and Results

To determine if this project was a success, the power delivered to the grid by the shorted rotor induction machine was compared to the power delivered to the grid by the DFIG (initially without phase angle control). The power delivered was compared over a range of rotor speeds, 70% $n_{sync} \leq n_m \leq 130\%$ n_{sync} (±30% of synchronous speed). Due to the grid frequency and the number of poles in the induction machine, the synchronous speed of the rotor is approximately 1500 rpm. Thus, the amount of power delivered was compared from 1020 – 2010 rpm. Figure 11 shows the power delivered to the grid over rotor speeds of ±30% synchronous speed.

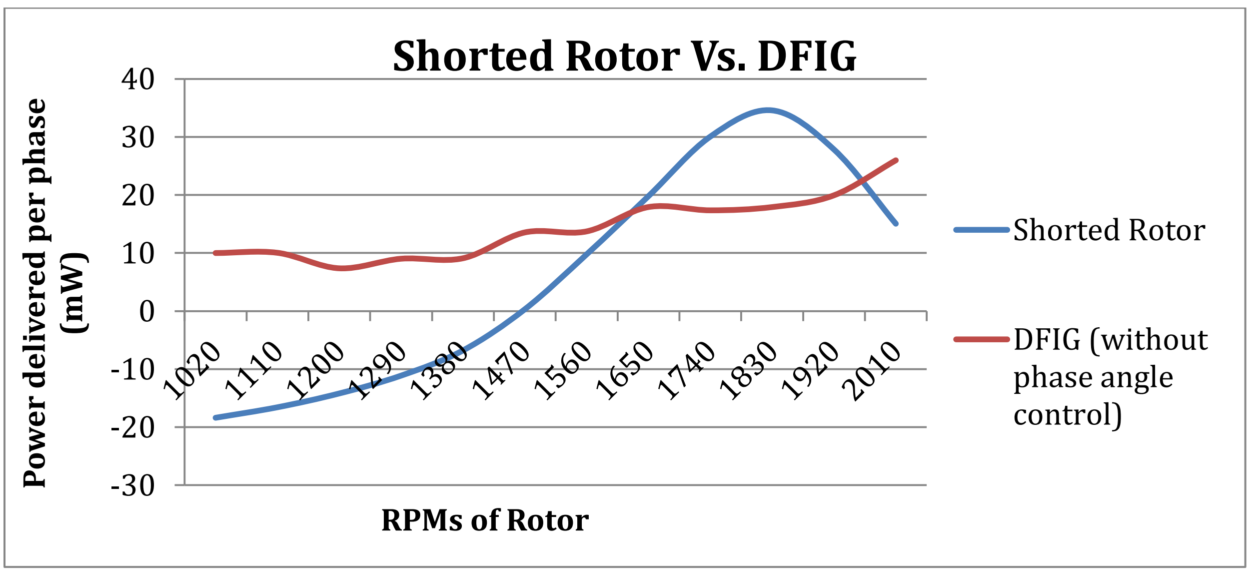

Figure 11: Standard Induction Machine (Shorted Rotor) power delivered to the grid compared to the DFIG (without phase angle control)

From Figure 11 it is easy to see that the DFIG delivers power to the grid when the rotor is spinning slower than synchronous speed while the standard induction machine is unable to. This is encouraging because it means that a wind turbine that uses a DFIG can deliver power much more often than one that uses a standard induction machine.

However, the standard induction machine has a higher peak power than the DFIG does. To determine which is more efficient, it is assumed that the wind turbine turns the rotor at each frequency an equal amount of time. If this is true then the DFIG delivers an average of 8.5 mW per phase (59%) more than the standard induction machine. If it is also assumed that the standard induction machine is disconnected from the grid (and thus delivers no power to the gird) when the rotor is turned slower than synchronous speed, the DFIG still delivers an average of 3.2 mW per phase (22%) more than the standard induction machine.

The maximum power point tracking also needed to be tested. The amount of power delivered to the load was evaluated over the same range of rotor speeds. For the maximum power point tracking to be successful, it needs to deliver more power than without the maximum power point tracking. Figure 12 shows the power delivered by the DFIG with and without the maximum power point tracking.

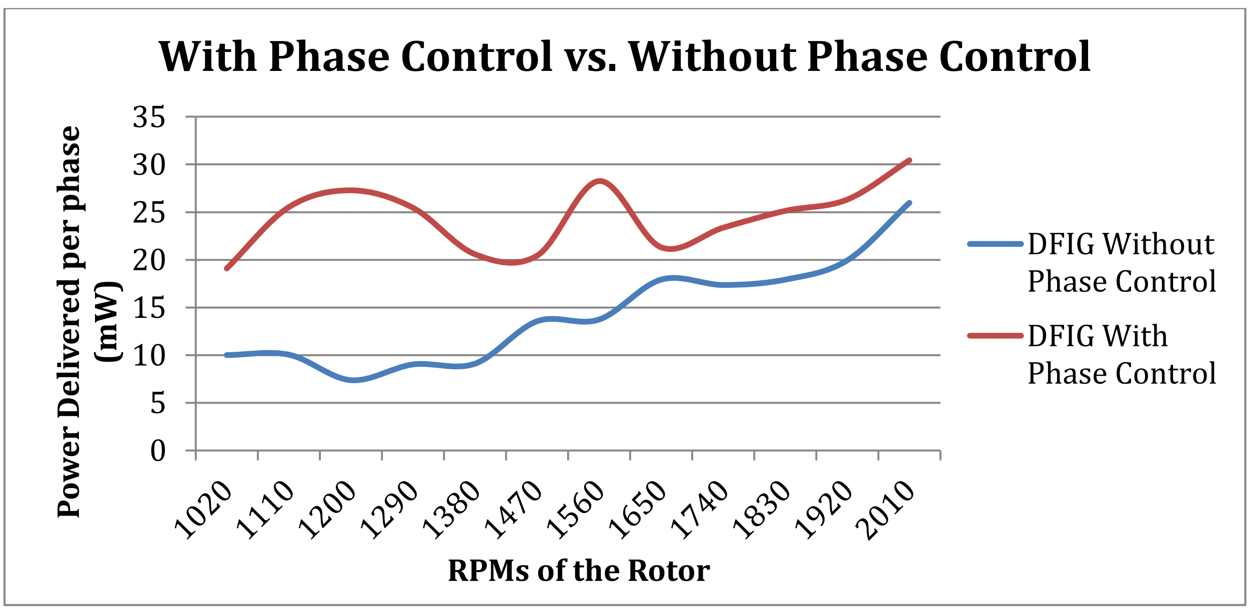

Figure 12: DFIG (with phase angle control) power delivered compared to DFIG (without phase angle control)

It is clear that the DFIG with phase control delivers more power than without phase control. The DFIG with phase control delivers on average 10.1 mW per phase (41%) more power than the DFIG without phase control. Now the DFIG with the phase control is compared to the standard induction machine. If it is assumed that the wind turbine turns the rotor at each frequency an equal amount of time the DFIG with phase control delivers an average of 18.6 mW per phase (76%) more power than the standard induction machine. If it is also assumed that the standard induction machine is disconnected from the grid when the rotor is turned slower than synchronous speed, the DFIG delivers an average of 13.3 mW per phase (54%) more power than the standard induction machine. A comparison of the DFIG with the maximum power point tracker, without the maximum power point tracker and the standard induction machine can be seen in the Appendix Figure A-2.

7. Production Schedule

During fall term research was done to understand how a DFIG works. Experiments were also done to help better understand how PWM works. Over winter break experiments were conducted to classify the DFIG and get comfortable working with the DFIG.

Winter Term:

Week 1:
- Testing with ordered PCI card that turned out to not be compatible with MATLAB or Simulink.

Week 2
- Install PCI card acquired from Professor Hodgson.
- Construct PWM Circuit.

Week 3
- Test PWM Circuit using only hardware to make sure it was operating correctly.
- Test PWM Circuit using the MATLAB program I previously created.

Week 4
- Meet with Professor Hodgson about Real Time Window package in Simulink.

Week 5
- Make PWM in Simulink using the Real Time Windows package.

Week 6
- Make frequency of desired sine wave calculations in Simulink.

Week 7
- Test and trouble shoot the control system.

Week 8
- Power Analysis tests
- Make Poster
- Practice Presentation

Week 9
- Write Paper

Week 10 – Finals Week
- Design and troubleshoot the maximum power point tracker.
- Write Paper

More work will be done in the spring term. The tachometer will be attached to the DFIG so that a faster maximum power point tracking can take place. The tachometer will also remove the need for the user to monitor the rotor speed. The GSC will also connected to the RSC.

8. Cost Analysis

The major cost in this project was the wound rotor motor with the windings brought out. The other parts that were purchased for this project were MOSFETs, Diodes, and a tachometer. A PCI Card was also ordered, however, it was not compatible with MATLAB so we used a PCI Card that another faculty member had and was willing to lend out. The total cost of the Parts that were ordered for this project can be seen in Table 1 below.

Table 1: Cost of Parts

Wound Rotor Motor	$2,000
MOSFETs (p – channel)	$40
MOSFETs (n-channel)	$25
Diodes	$18
PCI Card	$320
Tachometer	$81

9. Users Manual

9.1 Connecting the Control System

Every gate of the MOSFETs in the PWM circuit needs to be connected to an output of the control scheme. One of the stator windings also needs to be connected to the input of the control scheme so that the maximum power point tracker can determine if the power has increased or decreased. The output from each of the PWM circuits needs to be connected to one of the rotor windings.

9.2 Control System Settings

Open up the control scheme in Simulink from within MATLAB. Since there isn't a tachometer to keep track of the speed of the rotor, measure the speed of the rotor by using a handheld photo tachometer. Input the number of RPMs into the box that says *DFIG rpm*. Then click the *Incremental build* button to load it into the real time window. Once it is built click on the *Connect To Target* button then the *Start real-time code* button. The DFIG should now be running.

10. Conclusion

10.1 Goals

The goal of this project was to determine if it would be feasible to use a Doubly Fed Induction Generator in a small-scale wind turbine. Using a Doubly Fed Induction Generator would be feasible if it was able to deliver at least comparable amounts of power to a standard Induction machine. It must also be able to deliver power to the grid when the rotor is spinning at sub-synchronous speeds. Since both of these goals were met, a DFIG is a feasible option for use in a small-scale wind turbine.

To meet these goals the control system of the Grid Side Converter had three tasks. Those tasks were to determine the desired sine wave frequency to apply to the rotor windings so that minimal ripple would be added to the grid; find the maximum power point by changing the phase shift of the desired sine wave that is applied to the rotor windings; and converting the desired sine wave into a PWM signal.

10.2 Improvements

To improve this project a tachometer could be added. This would allow for automatic updates of the rotor speed within the Simulink program. This would also remove the need for a user to manually enter the rpms of the rotor into the Simulink program. The tachometer would also allow the program to monitor the rotor position. Knowing the rotor position would eliminate the time consuming process of finding the maximum power point because the correct angle of the desired sine wave could be calculated.

These two benefits of adding a tachometer would make the program much smoother because the whole Simulink program would be a closed loop, meaning it

wouldn't require any inputs from the user, which is more realistic. It would also make its reaction to changes in wind speed much quicker then the hill-climbing technique.

Adding the GSC and DC Link would make the DFIG self-contained. This is important because the DC voltage source is currently adding some power to the system. Once the system is self-contained a power flow analysis could performed. This would allow a determination of which direction real and reactive powers are flowing through the control system.

Once all of the parts of this project are finished and tested, the system should be scaled up so that it could be tested on the actual grid. A better understanding of the project feasibility could be determined if connected to an actual operating wind turbine. This would help determine how important a being able to operate at sub-synchronous wind speeds is. The amount of power delivered when using a DFIG could be compared to how much power is delivered when using a shorted rotor induction machine. This would help determine if the extra upfront money that is put into the control system would pay for itself in power delivered.

10.3 Lessons Learned

This project has shown that some of the longest delays come from unexpected places. In this case finding an IO board /PCI chip that could operate at a fast enough rate, in real time and was compatible with MATLAB was one of the biggest hang-ups. To find the winning combination for the needs of this project three different IO boards/PCI cards with programming in MATLAB and two different Simulink packages were explored in different combinations.

Some of the smallest mistakes have lead to the most puzzling results. For this project the most baffling mistake came because of the way the input to the PCI card was being protected. The protection scheme ended up loading down the generator. This made it seem like the generator wasn't putting any power into the grid no matter what currents were applied to the rotor. It took many hours of problem solving and testing to find the error.

11. References

Behr, Peter. "Will Politics Slow the Wind?: Scientific American." *Will Politics Slow the Wind?: Scientific American*. Scientific American, n.d. Web. 20 Nov. 2012. <http://www.scientificamerican.com/article.cfm?id=politics-of-wind-power>.

Brown, Donald. "Ethics and Climate." *Ethics and Climate*. N.p., 27 Aug. 2012. Web. 20 Nov. 2012. <http://blogs.law.widener.edu/climate/2012/08/27/wind-power-ethics/>.

Chuanwei Yang; Hui Liang; Jiuchun Jiang; , "Modeling and Simulation of AC-DC-AC Converter System for MW-Level Direct-Drive Wind Turbine grid Interface," *Power Electronics Specialists Conference, 2006. PESC '06. 37th IEEE* , doi: 10.1109/PESC.2006.1711994
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1711994&isnumber=36090

Datta, Rajib, and V. T. Ranganathan. "Method of Tracking the Peak Power Points for a Variable Speed Wind Energy Conversion System." *IEEE Transactions on Energy Conversion* 18.1 (2003): 163-68. Print.

"Do Wind Turbines Cause Health Problems?" *HowStuffWorks*. N.p., n.d. Web. 20 Nov. 2012. <http://science.howstuffworks.com/environmental/green-science/wind-turbines-health2.htm>.

Fletcher, J. Yang, J. (2010). Introduction to Doubly-Fed Induction Generator for Wind Power Applications. Nathwani, J. Ng, Artie., Paths to Sustainable Energy (259-278).: In Tech Publishers.

Hu, Zhouxing. "Development of Laboratory Doubly Fed Induction Generator For Wind Energy Research." (n.d.): n. pag. Web. <http://soar.wichita.edu/dspace/bitstream/handle/10057/3310/t10019_Hu.pdf?sequence=1>.

Kassakian, “ac/ac Converters”, in *Principles of Power Electronics*, Reading, USA: Addison-Wesley Publishing Company, 1991, ch.10, pp.237-245.

Mohan; Undeland; Robbins, “Line-Frequency Phase-Controlled Rectifiers and Inverters: Line-Frequency ac □□Controlled dc,” in *Power Electronics*, second edition. New York, USA: John Wiley & sons, inc, 1995, ch. 6, pp. 121-153.

R. W. Erikson, “Line-Commutated Rectifiers,” in *Fundamentals of Power Electronics*, second edition. New York, USA: Kluwar Academic/Plenum Publishers, 2001, ch. 17, pp. 609-630.

Tapia, A.; Tapia, G.; Ostolaza, J.X.; Saenz, J.R.; , "Modeling and control of a wind turbine driven doubly fed induction generator," *Energy Conversion, IEEE Transactions on* , vol.18, no.2, pp. 194- 204, June 2003
doi: 10.1109/TEC.2003.811727
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1201089&isnumber=27039

"The Wind Power Problem." *Environmental Problems with Wind Power and Wind Energy*. N.p., n.d. Web. 20 Nov. 2012. <http://www.wind-power-problems.org/wind-power-environmental-problems.html>.

Thiringer, Torbjorn. "Control by Variable Rotor Speed of a Fixed-Pitch Wind Turbine Operating in a Wide Speed Range." *IEEE Transactions on Energy Conversion* 8.3 (1993): 520-26. Print.

"Wind-energy-economy." *Wind-energy-economy*. N.p., n.d. Web. 20 Nov. 2012. <http://www.noblepower.com/faqs/wind-energy-economy.html>.

Yongbo Yang; Xiaoming Zha; , "Aggregating wind farm with DFIG in power system online analysis," *Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International* , vol., no., pp.2233-2237, 17-20 May 2009
doi: 10.1109/IPEMC.2009.5157774
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5157774&isnumber=5157395

Zhang Yingchao; Zhao Zhengming; Lu Ting; Li Long; , "Direct power and torque control for three-level NPC based PWM ac/dc/ac converter," *Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International* , vol., no., pp.1780-1784, 17-20 May 2009
doi: 10.1109/IPEMC.2009.5157682
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5157682&isnumber=5157395

12. Appendix

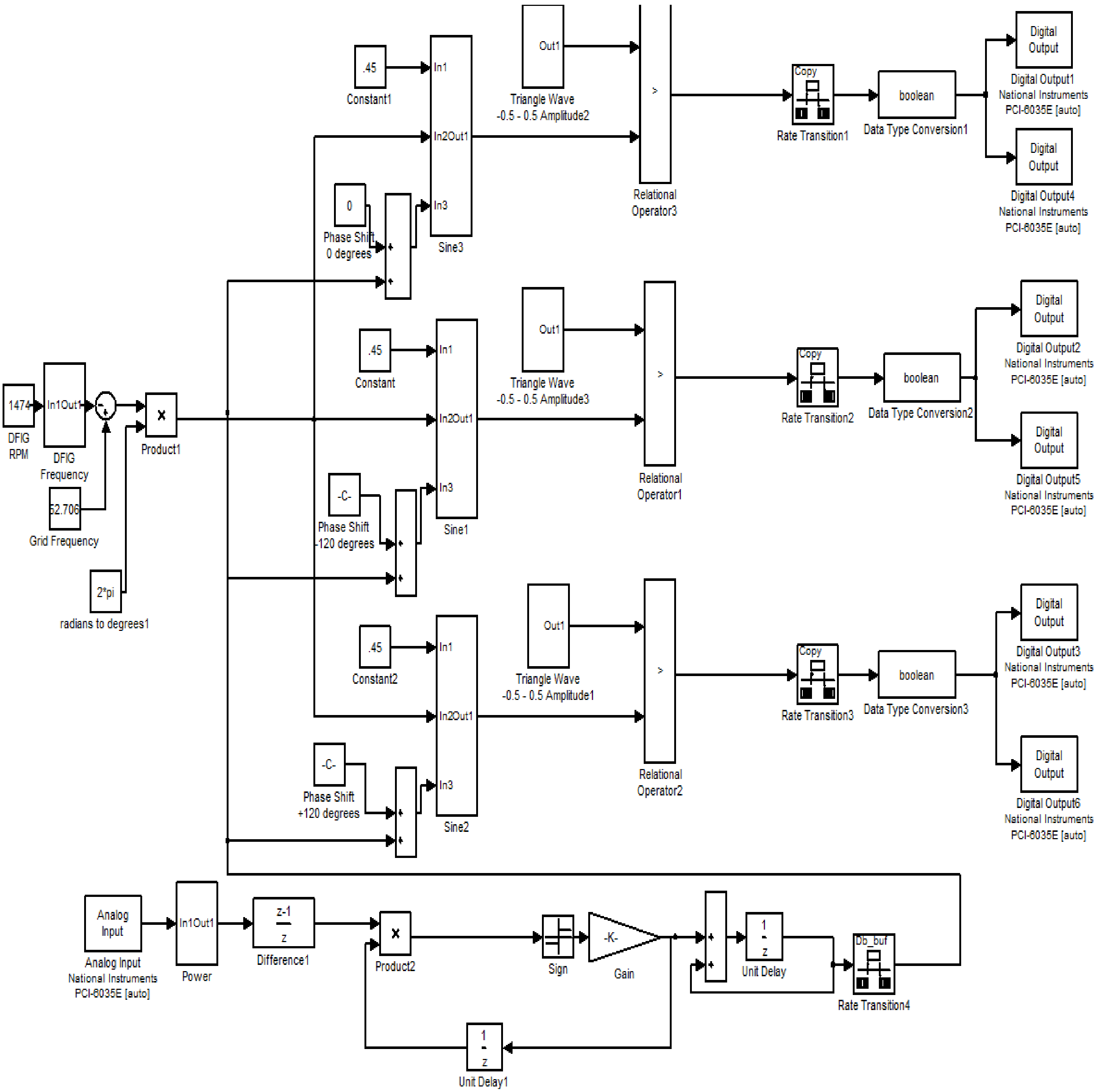

Figure A- 1: The full control scheme for the DFIG

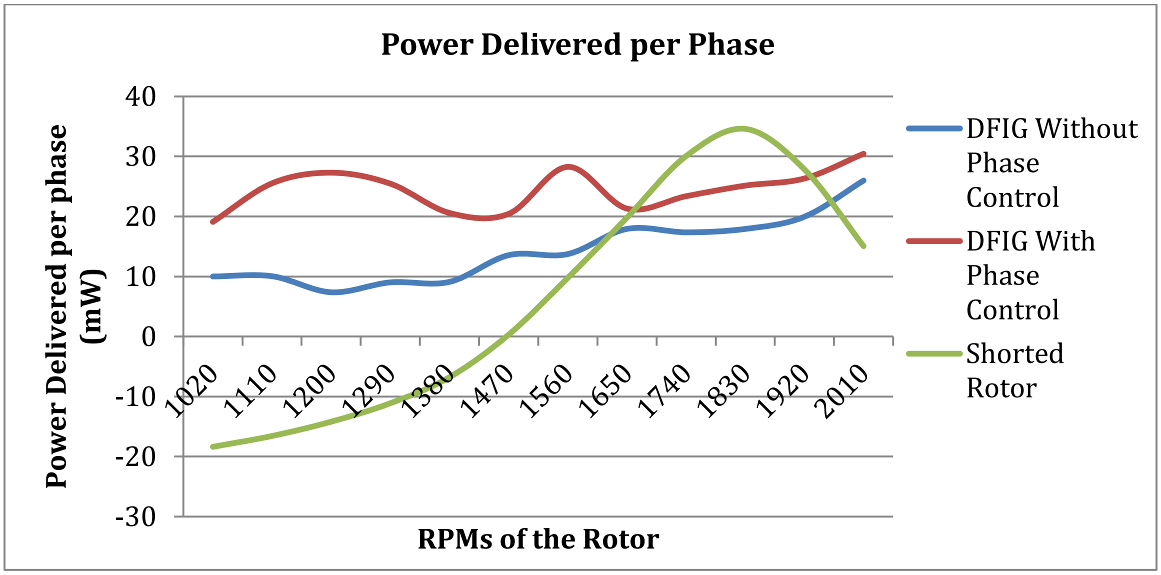

Figure A- 2: shows the power delivered to the grid for the DFIG when the maximum power point tracker is and isn't used and for the standard induction machine (shorted rotor).