Low Cost Inverter for Stand-Alone Wind Turbine

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Abstract

This interim report details the concept design and development of an electrical system for a Low Cost Stand-Alone Wind Turbine. This system is intended to provide a 240Vac 50Hz output, based on a mechanical wind turbine design developed at the University of Newcastle. To achieve this, the electrical system comprises of an induction generator, an AC to DC conversion circuit, a Battery bank and a 240Vac converter system. This report covers the design of the concept electrical system and details the progress in developing an induction generator model.

It is intended that this interim report will provide a basis for the final report on the electrical system of the Low Cost Stand-Alone Wind Turbine.
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Chapter 1

Introduction

1.1 Background

A 5kW wind turbine has been designed at the University of Newcastle. This wind turbine uses fixed-pitch plywood blades to drive an induction machine through a gear. This gear increases the speed of the shaft to improve the machine’s energy conversion performance.

The wind turbine mechanical system requires an electrical system to provide the required power output. More specifically, the electrical system is required to operate the induction machine as a generator and to deliver a 240Vac output. The wind turbine also requires an electromagnetic braking circuit to apply the machine brake in extreme weather conditions. A load torque is also required to assist in limiting the blade speed during the designed wind conditions.
1.2 Scope of Work and Goals of the Project

1.2.1 Scope of Work

The scope of work for this project is concisely described in the list below:

- Develop a model of the electrical system using the Simulink environment of the Matlab software package
- Design a method of reliably starting the generation mode of the induction generator
- Design a rectifier and battery charger circuit supplied from the induction generator
- Design a battery bank to provide adequate storage to improve the continuity of the power supply and also be able to be charged from the battery charger mentioned above
- Design a 240Vac converter using the above battery bank as an energy source
- Design a circuit to monitor the speed of the blades and apply the electromagnetic brake on the induction machine when the blade speed is higher than allowed for in their design
- Design a circuit to apply a load torque on the induction generator to assist in speed control of the blades within the design operating conditions.

1.2.2 Goals of the Project

The goals of the project are also most concisely defined as:

- To develop a working prototype of the electrical system that provides a 240Vac output from an induction machine
- To minimize the production cost of the system by using low-cost components through intelligent design
- To allow the engineer to develop project design skills and provide a useful outcome.
1.3 Report Outline

Now that the background, scope of work and goals of the project have been outlined, the remainder of this interim report will discuss the design development of the electrical system for a wind turbine.

Chapter 2 will introduce the overall electrical system design and show the breakdown of the system into its major components. Chapter 3 will discuss the development of the induction generator model in detail and provide concepts and considerations for development for each of the other major components in the system. Chapter 4 will discuss the project status and the expected pathway to achieving the goals of the project by the project delivery date.
Chapter 2

Design Outline

The purpose of this chapter is to provide an overall view of the wind turbine electrical system. The system has been broken down into smaller sections of work focused around the major components. This breakdown can be seen in figure 2.1. This figure also shows the basic links between the components. A brief description of the component links will now be discussed.

The induction Generator block in 2.1 provides the link between the mechanical and electrical systems. It takes the torque and rotational speed from the blades and provides an electrical output. This output determines most of the major design decisions in the system as the output of the generator is the power source for the system. The electrical output is the fed to the rectifier circuit which as the name describes, rectifies the three phase output from the generator to DC. This provides the correct voltage for charging the batteries and it is also the source for the blade speed control resistor. The batteries then provide the electrical source for the DC to AC converter which is responsible for the 240Vac 50Hz output that is the standard domestic power supply in Australia.
Figure 2.1: Project Breakdown
Chapter 3

Design Details

3.1 Induction Generator

The induction generator forms the basis of the wind turbine electrical system. It performs the task of transferring mechanical energy, in the form of rotation, into electrical energy. The use of an induction machine to perform this transfer provides some interesting electrical design challenges. To determine the output from the induction generator and to test various design ideas, a model of the induction generator is required. The remainder of this chapter is going to discuss the background, modelling methods and progress in the development of an induction generator model.

3.1.1 Background

The concept of modelling induction machines is introduced to electrical engineering undergraduates at almost all universities. ELEC3100 Electricity Utilisation taught at the University of Newcastle is a good example [2]. Using this course as a reference, the concepts of magnetising and leakage inductance are shown in Figure 3.1 which is the lumped circuit equivalent for a transformer. Electrical machines are generally considered as rotating transformers and the rotating component is generally introduced in two ways. Firstly, the Ideal Rotating Transformer (IRTF) concept, which is outlined in [2] and was developed by Duco Pule. This method uses an IRTF module which effectively adjusts the angles between phasors when converting from the rotor to the stator, and this adjustment is based on the slip frequency in the case of induction machines. An example of this in Simulink is shown in Figure 3.3.
Figure 3.1: Transformer per phase Equivalent circuit. Source [4]

Figure 3.2: Induction machine per phase Equivalent circuit. Source [4]

Figure 3.3: IRTF Model in Simulink. Source [2]
The second and more traditional approach is to use equivalent circuits. This method develops a per phase equivalent very similar to the transformer circuit shown in Figure 3.1 but uses a variable load resistance that represents the change in slip frequency. Refer to Figure 3.2 for an example.

Unfortunately, both methods use phasors to model the induction machine and as a result can only be used for steady state analysis. Due to the application of the induction machine in the wind turbine, dynamic analysis is required. For dynamic analysis, a more fundamental approach referred to a the generalised theory for electrical machines is required. This theory will now be briefly outlined.

**Generalised Theory for Electrical Machines**

The basis for the generalised theory for electrical machines is the DQ analysis technique. This essentially converts a three phase machine into a two phase machine. The benefit of this conversion is to create phases that do not mutually couple with other either on the stator or the rotor. This is achieved by assigning one phase, the direct axis (D), which is by convention aligned with the x axis. The quadrature axis (Q) is then assigned 90 electrical degrees form the D axis. Figure 3.4 shows the DQ representation of the stator.

The DQ representation of the induction machine allows for equations to be developed using Kirchhoff’s Laws and applied to the D axis and Q axis for both the stator and the rotor. This is achieved using equivalent circuits similar to Figure 3.2 discussed previously. Refer to [3] for further information. The result of these equations when combined into a matrix form is known as Park’s transformation which is shown in Figure 3.5. Most of the units should be familiar and therefore somewhat self-explanatory, with the exception of M. This unit is referred to by [3] as the ‘speed voltage’ and it represents the changing voltage from the changing mutual inductance between the stator field and the rotor field as a result of the rotor’s motion, represented by theta. The component represents the main reason for using this approach in modelling the wind turbine as it allows for the changing mechanical input from the blades to be modelled in a time dependant manner.
Figure 3.4: Three Phase to DQ conversion. Source [5]

Figure 3.5: The Park Transformation. Source [3]
3.1.2 Self Excitation

Now some mathematical background for the general model has been developed, the model requires further information to represent the machine and its application. In the configuration of an induction machine as a stand alone generator, it was found that self excitation was required to start the energy conversion process. Using a particularly relevant reference in [1] as a guide, capacitors are required between phases of the stator of the induction generator to store energy in the self excitation process. This capacitance is added to Park’s transformation by introducing a C element into the RL elements. Refer to [1] for a complete illustration.

Now the value of capacitance has to be obtained. Once again using [1] as a guide, Park’s transformation is resolved into 8th order differential equations. By solving the denominator for positive real roots we achieve values of capacitance that will guarantee self excitation for the parameters of the particular induction machine used.

At this stage it is useful to note some of the assumptions in the mathematical model. All of the values of inductance, capacitance and resistance with the exception of the 'speed voltage' component have been assumed to be values independent of electrical frequency. This is discouraged by Grantham in [1] but has been chosen to attempt to simplify the model. The other important assumption is that infinite permeability magnetic material has been assumed, meaning that there is no saturation for magnetic components. This has an important implication for the generator model as without self excitation there is no limiting factor for the self excitation and therefore no steady state operating point for the generator model. This is intended to be resolved by adjusting the 'speed voltage component so that it saturates and limits the self excitation.

Now there is enough information for the model to be attempted in Simulink.

3.1.3 Modelling in Simulink

Given that we have a method for three phase to two phase conversion, implementing these function blocks in Simulink was relatively straightforward. Mohan [5] made the process simpler by providing the direct equations. Both three phase to two phase and two phase to three phase conversion blocks were created.

The process of modelling the Park transformation is far less trivial. Firstly, Simulink does not have an explicit matrix function and whilst it is possible to export and import to the Matlab workspace for matrix functionality, the number samples requiring this to occur does not suggest a positive outcome.
therefor the matrix must be solved into its 8th order differential equations for the unknowns, which in our case is the two stator voltages V1 and V2. Also, to start the self excitation process, a residual magnetism in the rotor must exist and this is being represented by a small voltage on Va and VA on the rotor. A similar approach is used in [5] to build a Simulink model for an induction drive and this is being used as a guide for the development of this model. At this stage modelling is not complete and further work is required to actually develop a working induction generator model.

3.2 Blade Speed Control

The blade speed control component of the wind turbine electrical system performs two main functions. Firstly, it limits the blade speed when battery charging is no longer required by switching a set of load resistors to the generator output. Secondly, the blade speed control monitors the blade speed and if the speed rises higher than the design conditions, an electromagnetic brake is applied to bring the wind turbine to a complete stop.

Voltage and current monitoring of both the generator output and the battery requirements will be used to determine the blade speed and when it is appropriate to turn on each function as discussed above.

Each function will now be outlined in more detail.

3.2.1 Load Resistors

The load resistors have been chosen as an economical way to provide load torque. The resistors will be required to consume up to 5kW of energy from the generator and so will be quite large.

A number of connection methods are available. Of these the following three are the more obvious; Connection directly to the output from the generator, connection to the DC supplied from the rectifier circuit, or connection as a dummy load on the 240Vac converter. In addition, the choice of relay switching or controlled switching solution provides more variety in connection options.

The current concept is to connect a single multi-tap load resistor on the DC supplied from the rectifier circuit using relay switching. In comparison, connection directly to the generator output requires a balanced three phase resistor circuit which will require two more, albeit smaller, resistors than a single phase solution. Also, using the DC supplied from the rectifier circuit, reduces the duty cycle on the batteries and the 240Vac converter, which should result in a longer life cycle.
Relay switching, whilst limited when compared to a semiconductor controlled solution, provides a low cost method of connecting the resistor into the circuit. To try to improve control over the amount of load applied, two or even three stages of resistance may be used. Relay switching of DC circuits has its own limitations however, as breaking the circuit creates a larger arc than for equivalent AC circuits. Therefore a battery voltage limit of 110VDC applies from using this concept for the load resistor circuit, to allow for commercially available relays to be used.

3.2.2 Electromagnetic Brake

The electromagnetic brake is an integrated component of the induction machine. It is a spring loaded safety device that requires power to disengage the brake, so that in the event of a power loss, the brake is applied and the induction machine is brought to a standstill. The coil voltage of the device is predetermined when selecting the induction generator and it is anticipated that a 230Vac or 24Vdc coil will be selected, both of which can be easily accommodated, with 230Vac being the preferred choice. Control of the coil will be determined using voltage monitoring as noted above, with the controller for the 240Vac converter being used to control the switching and to activate an alarm. A manual brake application push button will also be hard-wired to the brake coil for safety reasons.

3.3 Rectifier Circuit

The function of the rectifier circuit is to convert the output from the generator into a battery charger. Two main methods for this conversion have been considered. Firstly, the use of a controlled rectifier, which uses a controller and semiconductor switches to produce a DC output and secondly, the use of power diodes configured for three phase rectification. Each method will now be outlined in more detail.

3.3.1 Controlled Rectifier

The controlled rectifier uses a controller to monitor the incoming three phase voltages and currents and determines a switching method for a set of semiconductor switches to produce the desired DC output. The controlled rectifier also requires isolation transformers, inductors, capacitors and resistors in various parts of the design to achieve the desired outcome. Comparison of the component requirements with the power diode option clearly shows the higher cost of this method, with the advantages
being a smoother DC output with a voltage that can be either higher or lower than the incoming supply.

### 3.3.2 Power Diodes

The power diode is the preferred concept at this stage of the project. The primary reason for this is cost. The power diodes introduce more limitations to the design when compared to the controlled rectifier however. A higher DC ripple is produced that will require further filtering in the rectifier circuit prior to connection to the batteries. Also, because it consists of passive components, control of charging current and output voltage is very limited. Therefore because of this selection, the charging battery voltage must be less than the generator output voltage and the battery capacity cannot require more than 5kW of power with flat or the induction generator is a risk of stalling. Whilst the stalling statement is not completely accurate, it provides a conservative target to focus on outside the effect of mechanical inertia and the wind conditions of the day.

### 3.4 Batteries

The need for batteries with a wind turbine is obviously due the unreliable source of wind. Choosing the capacity and voltage is often determined by other factors in a system, as it is in this concept design. Due to the choice of using the DC rectifier circuit to supply the load resistors for the blade speed control outlined in section 3.2, the battery voltage for the concept design is 110VDC. Also, because of the choice of power diodes, the maximum capacity has also been set. Refer to section 3.3.2 for more information.

Some outstanding issues still remain however, with one of the main problems being the anticipated voltage reduction from 200VDC (the rectified induction generator output voltage) to 110VDC. A simple drop down resistor would work, but would be highly inefficient. Other methods including a total concept review are currently underway to resolve this issue.

At this stage the choice of actual cell has been focussed on either Nickel Cadmium (Ni-Cad) or Gel type sealed lead acid batteries. Both represent higher cost than conventional lead acid batteries, but offer some distinct advantages. Ni-Cad batteries maintain their output voltage during discharge for longer than a conventional lead acid battery and this will assist the converter in achieving its desired output voltage. Gel cell batteries provide a far lower maintenance cycle when compared to standard lead acid batteries as they do not consume water or discharge hydrogen gas during normal operation.
like standard lead acid batteries.

Further work is required to determine the final calculations for the batteries and to develop enough information to allow for their purchase for the prototype.

### 3.5 Converter Circuit

The converter design has not been investigated at this stage, but with the concept design having a 110VDC output from the batteries, it is expected that a ’boost’ switch mode topology will be used. An M16C micro controller has been selected to control the boost converter due to familiarity with the chip and its coding requirements. Further work on this project component may show that other alternatives are more suitable and these may be considered extensions to the project to refine the design.
Chapter 4

Conclusion

Development of the induction generator has been slower than expected, but it is anticipated that most of the major hurdles have been crossed and final development will be in the near future. A small amount of time will be spent verifying this information with the actual drive as the overall system requires further development and refinement. In particular, time spent on developing the 240Vac is required as it is expected to be a lengthy development process.

At this stage the goal of a working prototype electrical system for the wind turbine still seems attainable, but a significant amount of work is still required.
Bibliography


