CONTROL SYSTEM FOR SMALL INDUCTION GENERATOR BASED WIND TURBINES

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Control System for Small Induction Generator Based Wind Turbines

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Abstract

The unpredictable nature of wind makes the design of wind turbines control system a challenging task. Wind turbine system control becomes more difficult when the system is required to connect to the grid. The major issues include connection standard, control system simplicity, cost, reliability, required instrumentation and modes of system operation. A low cost control system and associated instrumentation development is very important for the commercial success of a small grid connected wind turbine. The proposed PIC micro-controller based control system is a good candidate for 3 kW or less grid connected wind power systems.

The purpose of this thesis is to design a control system for small induction generator based grid connected wind turbines. A PIC16F877 micro-controller is used to connect/disconnect the wind turbine generator to the grid based on real time measurements. The controller is designed and tested for grid connected mode and off-grid mode. The system controller based on the measurements takes decision for grid connection/disconnection or maintains the connection of the system with the grid. Designed controller also takes care of the islanding situation. Such situation occurs in the system while wind is enough to produce power but the grid is absent. The proposed controller will never connect the wind turbine to the grid when grid is absent hence islanding situation will never occur. Low cost instrumentation is also developed to measure the system parameters.

The designed controller is tested in a laboratory environment using a wind turbine simulator. Wind turbine simulator is an effective platform to evaluate the performance of the wind turbine control system in all possible situations in the lab environment. The proposed wind turbine simulator is based on a 3 kW DC motor. A separately excited DC motor is controlled so that its shaft behaves as a wind turbine rotor. A PI controller is designed which makes sure that the DC motor is producing torque same as wind turbine rotor torque at various wind speeds.

Soft-starter is also designed to reduce inrush current or surge in current while achieving a proper synchronization between the wind turbine generator and the grid. The designed soft-starter successfully limits the high inrush current during the connection of the wind turbine system to the grid. An experimental investigation is done to find out suitable values of the power resistors for soft-connection of a small wind turbine system to the grid. The designed soft starter limits the initial surge current 1.62 times the rated current of the induction generator.

While grid is absent, the system controller ceases the power delivery to the grid and connects the wind turbine system to a dump load. However, due to the variation in wind speed the voltage at the load terminal can vary. An electronic PI controller based on phase control relays is developed to regulate the voltage across the dump load while grid is absent.

The applicability of the proposed system controller for small wind turbines is demonstrated through a number of lab tests. The results show the designed control system is able to control a 3 kW induction generator based wind turbine both in grid connected and off-grid mode.

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List of Symbols

A = area swept out by the turbine blades

C_q = Torque coefficient

C_p = Power coefficient

$C_1, C_2..$ = Capacitors

D_0 = Relay driving signal for *relay_1*

D_1 = Relay driving signal for *relay_2*

D_2 = Logic signal for solid state relay

$e(t)$ = Error between expected and actual control variable

$e(k)$ = Error at k^{th} step

$e(k-1)$ = Error occurs in previous step

f_{ng} = Error occurs in previous step

f_g = Frequency on grid side

I = Current flow between IG and grid

K = Gain which is equal to proportional gain of the PID controller

K_u = Ultimate gain

k = Discrete time step

P = Power flowing between IG and grid

P_{mech} = Mechanical power output at the wind turbine

P_u = Ultimate period

R_t = Radius of the rotating turbine

$R_1, R_2 ...$ = Resistances

t = time in seconds

T_{av} = Average torque produced by the wind turbine

T_{ref} = Reference torque produced by the wind turbine

T_I = Integration time of the controller

T_D = Derivative time of the controller

T_o = Sampling time

u_w = Wind speed

$u(t)$ = Output of the controller at any instant t

v_{ig} = Voltage on generator terminal

v_g = Voltage on grid side

V_s = Output voltage of the speed sensor

V_{TS} = Torque sensor output voltage

V_{ref} = Reference voltage for the electronic PI controller

ω = Generator speed

ω_m = Angular velocity of the turbine

τ = Instrumentation RC time constant

λ = Tip speed ratio

ρ = Air density

List of Abbreviations

AC = Alternating current

ADC = Analogue to digital converter

CB = Circuit braker

CanWEA = Canadian Wind Energy Association

DC = Direct current

DAQ = Data Acquisition

DIO = Digital input output

DR = Distributed resources

area EPS = area electric power system

HP = Horse power

IG = Induction generator

IGBT = Insulated-gate bipolar transistor

IM = Induction motor

I/O = Input/output

MUN = Memorial University of Newfoundland

PC = Personal computer

PCR = Phase control relay

PI = Proportional integral

PID = Proportional integral derivative

PCC = Point of common coupling
PIC = Peripheral interface controller
PLC = Programmable logic controller
PWM = Pulse width modulation
RAM = Random access memory
RPM = Rotation per minute
RMS = Root mean square
SEIG = Self-excited induction generator
SWECS = Small wind energy conversion system
USB = Universal serial bus
VB = Visual Basic
WT = Wind turbine
WTE = Wind turbine emulator
WTS = Wind turbine simulator
WECS = Wind energy conversion system
ZN = Ziegler-Nichol's
RISC = Reduced instruction set computer
CPU = Central processing unit
TTL = Transistor transistor logic

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Chapter 1

Introduction

1.1 Background

Wind technology is one of the fastest growing renewable energy technologies in the globe. Technologies for wind power generation are rapidly expanding due to the high cost of energy derived from fossil fuel, nuclear fuel and environmental issues. A recent survey shows the booming wind energy markets around the world exceeded expectations in 2006. This takes the total installed wind energy capacity to 74223 MW, up from 59091 MW in 2005 (www.gwec.net).

Canada has a great potential for electricity generation from wind in North America because it has the longest coastline with wind resources. Canada is currently experiencing an annual 30% growth rate in wind energy development, a rate comparable to the global development. The recorded installed capacity in Canada until July 2007 is 1588 MW. The Canadian Wind Energy Association's (CanWEA) goal is for 10,000 MW of installed wind energy in Canada by the year 2010 which is sufficient cater for 5% of Canada's electricity demand (www.canwea.ca).

Generation of electricity using wind energy is extremely significant for many remote or isolated places away from the grid. However, after net-metering regulations, public interest in small-scale grid connected wind power generation has increased. Net-metering is the exchange of energy between consumer and the main electrical grid. Net-metering is one of incentive programs since it allows the customer ability to offset power consumption up to 100% at the full retail value over the regular billing period (usually one month). Excess power produced is either granted to the utility with no buy-back, purchased by the utility at the avoided cost, or purchased at the average retail rate (www.nrel.gov). In net-metering situation, consumers also do not require to purchase expensive batteries or a backup generator, which increase the install cost of renewable energy systems (www.energy.gov.on.ca). Moreover, small wind turbines are less expensive, engaged with a very few moving parts and they are generally designed for a long life (www.smallwindenergy.ca). They can be easily installed at the tower or roof tops with a smaller tower arrangement. Due to the increasing demand of the electricity generation from the wind energy and also with net-metering rules, current Research and Development (R&D) activities concentrate the investigation of the behavior of small grid connected wind turbines and specially its control.

Small grid connected wind turbines can operate with either fixed-speed or variable speed. Amount of energy that can be produced by a variable speed wind turbine is generally greater compared to a fixed speed wind turbine [1]. However the operation of a variable speed wind turbine system is difficult and complex due to the complex pattern in the wind [2]. Such an arrangement will not be economically feasible in the context of a small wind turbine. This research focuses on the control system of a small grid connected wind turbine, which operates at a fixed speed with higher conversion efficiency. In generic, wind turbine produces electricity using wind and supply the generated power to users. Due to the stochastic nature of wind, a supervisory controller is essential for connection/disconnection of the wind turbine system to the grid. System control is required, not only for connection/disconnection, but also for maintaining connection between the grid and the wind power generator while wind turbine in operation. Several control modes are needed to be considered in designing control system for a grid connected system. Also due to the occurrence of high inrush or surge in current during achieving the proper synchronism between the grid and the generator, soft-connection strategy is essential. Soft-connection reduces mechanical and electrical stresses on the wind energy conversion system during the connection process of the generator with the grid. A wind turbine simulator (WTS) is also required to test the performances of the proposed controller before installation.

1.2 Motivation

Wind energy conversion system (WECS) is required to be directly connected to the utility grid in order to reduce the system cost. Grid connected system also reduces the dependence on the grid supply. Therefore the selection of a grid connection strategy and suitable control technique for the operation of a wind turbine system in different real time situations are the great motivating points for this research. There are three ways to connect the small wind turbine generation system to the grid [3], as shown in Figure 1.1. Option 1 in Figure 1.1 requires rectifier, batteries and inverter to connect the generator to the grid. Rectifier and inverter are also required to connect the generator to the grid in option 3. However, option 2 does not require such interfacing power electronics circuitry which is very significant for a low cost small wind energy conversion system. The direct connection of a wind turbine system to the grid using option 2 is less complex. This option can also provide higher efficiency than the other options because of no losses due to no such interfacing circuitry [4].

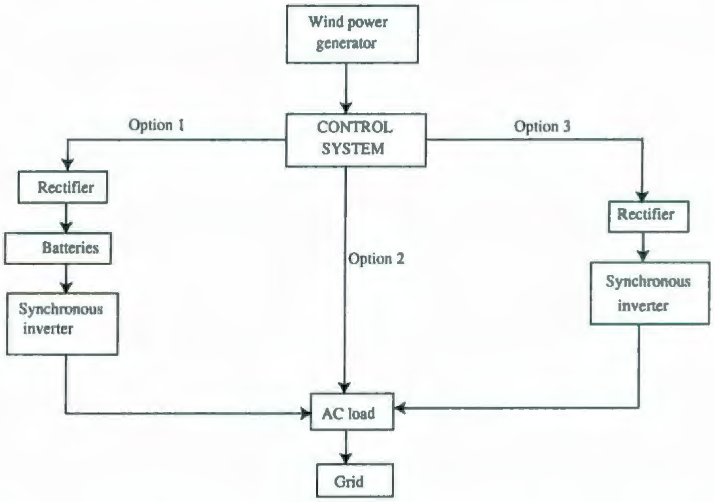


Figure 1.1: Grid connection topology for small wind turbine

Control system is an integral part of a wind power generating system for proficient operation of the unit. Design and implementation of control system for small grid connected wind energy conversion system is a great challenge. This research attempts the following issues to design control system for small induction generator based grid connected wind turbines.

- Choice of economical and feasible supervisory controller
- Controller action in the presence of wind and grid availability
- Controller action in the absence of grid but wind is enough to produce power
- Maintain grid connection/disconnection without sensing wind speed
- Over voltage and under voltage at the generator terminal
- Soft-connection between the wind turbine system and the grid
- Low cost system instrumentation design to measure system parameters

In order to address the above mentioned issues in designing control system, a prototype of a wind turbine in a laboratory environment is very important. A wind turbine prototype called a wind turbine simulator, designing is another challenge in this research. Following challenges are taken in consideration to design a wind turbine simulator.

- Impose the steady state wind turbine characteristics in a DC motor
- Design a torque controller for DC motor which makes sure that DC motor is operating as a wind turbine
- Test the simulator for fixed and variable speed of the wind

All of the above discussed challenges highly motivate to conduct this research.

1.3 Related Works

A small directly grid connected system with higher efficiency does not require complex power electronics for its control. However, realization of control strategy for grid connection operation in different real time situations is very important and further research is required to improve small grid connected wind turbines performance.

According to past research, proper control system made the wind turbine more reliable in wind power generation. A proper aerodynamic control of wind turbine will cause no extra pressure on the electrical and mechanical parts of the wind turbine system, thus increasing the ability to produce maximum power [5], [6]. Aerodynamic control techniques and its implementation has been found in [7], [8], [9], [10]. Extraction of maximum power controls was also found in [11], [12], [13], [14] for stand alone applications. For a small grid connected wind turbine system, this work assumes the system has no aerodynamic control strategy and the system that only produce maximum power at a specific wind speed.

In literature, some controllers are reported for small grid connected wind turbine applications. A controller developed by ENERTECH Corporation [15] connects the ENERTECH wind turbine to the grid only when winds are strong enough to make it behave as a generator, and disconnects when wind speed decreases to avoid that acting as a motorized fan. This control system had two major components, an anemometer, mounted on the tower, and a printed circuit board, in the control box. The control system consists of an anemometer at the tower top, a wind averaging unit, a wattmeter, a wind speed indicator, a solid state control, 3-way switch, mercury relay, and a printed circuit board in the control box. Measurement of average wind speed over periods of 20 to 45 seconds, as sensed by the anemometer, is used to connect/disconnect the wind turbine from the grid. The main issue with such wind speed measurement based controller is the requirement of a calibrated anemometer placed appropriately on or close to the wind turbine. Since an anemometer controls the cut-in and cut-out speed of the wind turbine, a poor positioning of the anemometer will significantly affect the performance of the wind turbine. The anemometer also requires twisted and shielded wire that is resistant to weathering in sunlight and deterioration underground. If it is not, electrical noise from an outside source can cause a contaminating frequency that will in turn cause the machine to turn on and off erratically. ENERTECH wind turbine is not in production for more than 20 years.

Another small wind energy converter named as "aeroSmart5" came into the market in early 2004 [16]. The system controller unit of aeroSmart5 has been designed by a development firm

"SMA Technologie". That microprocessor based system controller controls both the turbine and the connection to the power grid. The aeroSmart5 has been designed for passive stall operation in high wind speeds and there is no mechanical fail-safe furling mechanism. This type of power output control system was widely used during the years 1975-1995 for large grid connected wind turbines [17]. Unfortunately, the main drawback of this technology is when the connection between the generator and the grid trips out, the turbine will quickly become uncontrollable. Furthermore it will reach runaway rotational speed under insufficient passive stall design. In addition, the aeroSmart5 is designed to stop through an electromagnetic safety brake once the control unit detects a too high average power.

A 20 kW Gazelle wind turbine has been commercialized by Gazelle Wind Turbines Ltd [17]. The control of this wind turbine is based on the output power and the control is performed using a Programmable Logic Controller. A low cost induction generator requires a simpler control circuitry and such an arrangement cannot be recommended for a small low cost induction generator based wind turbine. ENDURANCE Wind Turbines is currently testing a prototype of a 3.75 kW induction generator based wind turbine which is expected to hit the market by the end of 2007 (www.windwardengineering.com/Endurance). Details of its control system are still unknown. This research proposes an economical micro-controller based controller which is easy to program and overcome the problems associated with the other controllers.

The above discussed controllers do not indicate its operation during islanding situation. Electrical system islanding occurs when the utility grid is removed but local sources continue to operate and provide power to local loads [18]. Unintended islanding is a concern primarily because it poses a hazard to utility and customer equipment, maintenance personnel and the general public [19]. Many techniques have been proposed to prevent islanding caused by Distributed Generators [20], [21], [22], [23], [24], [25]. As the proposed controller performs grid connection/disconnection based on the generator and grid parameters measurement, the controller can easily takes care of islanding situation. Another issue also needs to be considered for grid connected wind turbines is the soft-connection between the grid and wind energy conversion system while achieving proper synchronism. Soft-starters are widely used during the start up of induction motors/AC motors in different applications [26], [27], [28], [29], [30],[31], [32] to reduce mechanical stresses on the drive system and electrical stresses on the electrical supply. In wind power applications, directly connected squirrel cage induction generator requires to be equipped with soft-starter because wind turbines affect the power quality during the process of connecting a wind turbine system to the grid [33], [34], [35], [36], [37]. As the induction generator of a fixed-speed wind turbine is directly connected to the grid, a soft-starter is used to reduce the inrush current during connection. A soft-starter based on semiconductor devices [38], [39], [40], and power resistor [41] are reported in literature. Advanced soft-starter based on semiconductor devices are primarily designed for large wind turbine and also need to control the firing angle of the soft-starter elements. On the other hand, power resistor based soft-starter does not require such control. Although a power resistor based soft starter is described in [41], their limitation is the current limiting period taken by the external resistor is too long. This research proposed a power resistor based soft-starter where current limiting period taken by the resistors is very small, and very cheap scheme in the context of small grid connected wind turbine.

Grid connected system, compared with a stand alone system, does not guarantees a back up power in situations, when wind availability is low. However, a situation needs to be considered for utility connected system is the absence of grid while other sources are sufficient to produce enough power. In such situations, it assumes wind generator producing power more than the consumer demand and grid is not available. The system needs to dump the excess power to a dump load to maintain safe operations of the wind turbine. Such problem is also addressed in this research by simultaneous operation of the supervisory controller and an electronic load controller. Past studies on electronic load controller are found in [42], [43], [44], [45], [46] based on different techniques. Firstly, a rectifier chopper feeding a fixed resistive dump load [42], where dump power is controlled by varying the duty cycle of the chopper. As choppers receive power from a fixed voltage dc source using a rectifier, this arrangement can not be recommended for the directly grid connected system. Secondly, an

AC controller with a back-to-back thyristors feeding a fixed resistive dump load where firing angle varies power in the dump load [44], [45], [46]. In a phase controlled thyristor-based load controller [44], [45], the phase angle of back-to-back connected thyristors is delayed from 0 to 180 as the consumer load is changed from zero to full load. Due to a delay in firing angle, it demands reactive power loading and injects harmonics in the system. It further requires complicated driver circuits. Another electronic load controller based on anti-parallel insulated-gate bipolar transistor (IGBT) switches are used to control the dump load connection and disconnection only [43]. The technique shown in [42] is the only method applicable for wind energy applications, where as others [43], [44], [45], [46] are demonstrated for micro/pico hydro applications. This research deals with an alternative technique based on phase control relay to control the dump load. Proposed arrangement is simple because only one signal can operate three phase control relays for three phase system, does not require any driving circuit and safe the system from harmonic injection.

To carry out research on small wind energy conversion system, a setup of a controlled test environment with steady-state characteristics of the wind turbine is essential. Before building a real wind turbine it is important to know its expected behavior at varying wind conditions and also the effectiveness of various control strategies [47]. This can be achieved by developing a wind turbine simulator which will reflect the real behavior of a wind turbine. The main purpose of wind turbine simulator is to use as an aid to test real wind pattern variations in designing wind turbine control. Research on the control of wind turbine is progressing by implementing the control schemes in a simulator. These investigations are mainly performed on the 5 kW or more rated wind turbine [48], [49]. However, investigations need to be further extended to small grid connected wind turbines (3 kW or less) to properly understand and characterize the behavior and control of such wind turbines to provide clean power to the grid. Literature search indicates that a number of WTSs have been developed to simulate the wind turbine shaft for various purpose. More realistic simulator should have both the steady state and dynamic characteristics. Several simulators have been developed using steady state wind turbine models based on the power speed characteristics [49], [50],

[51], torque coefficient based wind turbine model [48], [52], [53], power coefficient and pitch angle based wind turbine model [54]. Researchers add dynamic behavior with the model in different ways. Elastic model of the turbine shaft [55]; mechanical balance equation [56], [57] for the turbine torque; and aerodynamic, oscillatory and dynamic torque to combine the wind turbine torque [58], [59] are found in literature. However, passive pitching mechanism and/or rotor blade inertia with the wind turbine model can be a more generalized approach for a small wind turbine system [60]. This research considers the rotor blade inertia for the wind turbine model which assumes the same as the rotor inertia of the DC motor and the induction generator. Above discussed simulators are based on various types of generators. Most cases wind turbines are based on permanent magnet type generators or field regulated alternators which are primarily designed for stand alone applications. This research extends the development of a wind turbine simulator system based on induction generator which is the best option for small wind turbine system.

1.4 Thesis Objectives

The main objective of this thesis is the design and test of an economical micro-controller based system controller for a small induction generator based wind turbine that can maintain the interconnection between the generator and the grid. It is also required to develop low cost system instrumentation for the measurements of the system parameters upon which the proposed controller operates.

1.5 Thesis Contributions

Followings are the summary of outcomes in this research.

1. Development of a wind turbine simulator to provide a test bed for the system controller. A discrete PI controller is designed to simulate a separately excited DC motor as wind turbine rotor.

2. Design and development of a novel micro-controller based system controller for small induction generator based grid connected wind turbine. Two different control methodologies (current and power feedback) were developed and tested.
3. Development of instrumentation to measure the system parameters and test the performance with the system controller.
4. Design and development of a novel control system during off-grid operation of the grid connected wind turbine.
5. Design and test of a power resistors based soft-starter for a small induction generator based grid connected wind turbine.

1.6 Thesis Outline

In chapter 2, the development of a small wind turbine simulator is presented. Design of a discrete PI controller is also presented which makes sure that the DC motor follows the reference torque produced by the wind turbine. A constant and sudden change in wind speed, and also a variable wind speed profile is fed to the wind turbine model during the test of simulator. The test results for these conditions are presented here.

In chapter 3, the selection of wind power generator, system instrumentation, operation modes of the controller based on wind speed and grid availability, and also typical installation requirements for grid connected systems are presented. The instrumentation for the measurements of voltages and frequencies from the generator and the grid sides, power and current flow between the induction generator and the grid are also presented. Instrumentation for soft-connection of the wind turbine system to the grid is also presented. A typical installation requirement for the grid connection system is also explained in this chapter.

In chapter 4, the selection of system controller, and its design and implementation issues are discussed. The operation of the control sequences in details with flow chart for current, speed and power measurements are presented. Phase control relay based electronic load controller design and operation is also presented while wind is available but grid is absent.

An investigation for implementing power resistor based soft-connection between the generator and the grid is also described.

In chapter 5, the performance of the micro-controller based system controller and developed instrumentation are presented. The algorithms for system connection based on voltages and frequency measurements, and system disconnection based on speed, current or power measurement is explained. An experimental test result for determining the suitable power resistors value and also suitable time difference between switching of two relays in soft-starter is presented. The test result of the phase control relay based electronic load controller for voltage regulation at the generator terminal is described. The results of the investigations prove that the proposed low cost micro-controller based system controller performs successfully for connection/disconnection of the system with the grid in different real time situations.

In conclusions, a summary of the research work in the thesis is presented. The outline of the contributions and achievements from this research work are also highlighted in chapter 6. The chapter also includes the recommendations for further investigations.

Chapter 2

Small Wind Turbine Simulator

Objective of this chapter is to demonstrate the development of a wind turbine simulator where it can be used to generate the torque output for a given wind dynamics. Such a tool is quite important to experiment, as there is no real wind turbine facility available to perform research. Secondly, it is possible to simulate all types of wind dynamic patterns to observe the robustness of the controller. Finally, performances of the proposed WTS are also presented in this chapter based on the experimental tests at various wind conditions.

2.1 Introduction

A WTS is fundamentally a prototype of a practical wind turbine in a laboratory environment. Past research on WTSs are described here in a brief.

A WTE is described in [47] for stand alone application, which consider the furling action for varying aerodynamic power of the wind turbine. The shaft torque of the DC motor is determined from the armature current, and the parameters of the DC motor were determined by experimentation. A gain scheduled digital PI controller is designed to track the theoretical rotational speed of the wind turbine rotor by the DC motor. A more generalized approach WTS design is found in [61]. The proposed DC motor based wind turbine emulator consists of a real time software simulator and an electromechanical tracking system. This approach provides a better flexibility to simulate the DC motor either in torque control or speed control mode by taking the reference from the used wind turbine model.

DC motor based WTS by considering torsional oscillation in the steady state condition is described in [59]. A buck converter supplied by a three-phase full-bridge diode rectifier was employed for controlling the armature current and consequently the torque developed by the wind turbine. This PWM dc-dc converter based WTE is able to reflect the gradient and the tower shadow effects in an effective manner.

A WTS using a separately excited DC motor rated at 7.5 kW is presented in [55]. Wind turbine model based on both the steady state and dynamic behavior is incorporated in this simulator. The steady state torque is passed through a three mass model which represents the wind turbine, gear box and generator moments of inertia and the elastic shafts connecting them. For mechanical power control, pitch angle control method is adopted with the wind turbine steady state model. The control is performed by controlling the speed of the separately excited DC motor.

A research by Manwell [62] on a hybrid system where the WTE is mainly designed based on the steady state characteristics of the wind turbine. In this work, a DC motor has been simulated to reflect the wind turbine behavior and the model of the wind turbine based on power coefficient vs. tip speed ratio curve. Aerodynamic torque of the wind turbine is used as a reference torque which is compared with the DC motor torque and based on these two measurements, the controller determines the torque of the WTE.

Pierik [63] described a passive pitching mechanism to the wind turbine model where the rotor dynamics are included. A separately excited DC motor is employed to simulate the wind turbine and the motor is controlled using armature current. A flywheel at the motor shaft that represents the inertia of a wind turbine rotor. Based on the difference of reference torque produced by the wind turbine and the torque given by the motor, the DC motor armature current is controlled.

Barrero [58]and Battaiotto [56] presented a WTE using a simpler wind turbine model. The DC motor is used to simulate the wind turbine characteristics by means of a armature current controller. Oscillatory, aerodynamic and dynamics issues of the wind turbine have been incorporated to reflect the torque dynamics [58]. However, the control strategy is implemented using dual DSP board which increases the emulator system cost.

AC motor based WTEs have also found in [49], [50], [51]. In [49], an induction motor (IM) which is rated at 125 HP is simulated. The wind turbine model is incorporated in the PC using static speed vs. power curve and no mechanical control is incorporated with the model. At any given wind speed, the operating point of the wind turbine is determined by the intersection point of load and turbine characteristics. The feedback from the IM motor has taken as torque and speed which determines the required torque for the wind turbine. The three phase IGBT converter is triggered on the base of the controlled stator current. Information about the mechanical power control has not been described. Further research has been carried out [50], [51] based on the rating of a 10 HP IM and using the same control strategy used in [49]. The problem with this research is that it does not represent any small wind turbine characteristics which are very significant for the design and development of small wind turbine industry. A cascaded mode control task has been implemented which increases the system complexity.

Previous studies on WTS is mainly focused on 5 kW or more rated wind turbines [48], [49]. Further research needs to be extended on small wind turbines (3 kW or less) to effectively understand and observe the behavior and to develop control systems of such wind turbines.

2.2 Wind Energy Conversion System

A typical wind energy conversion system consists a rotor, which transforms wind energy into mechanical power, a transmission system to obtain desired rotational speed of the shaft, an electrical generator, and finally a control system to produce clean power. A great deal of research has been carried out to prove the effectiveness of wind energy from large wind energy conversion systems but unfortunately not much research has been conducted on small wind energy generation systems. Wind turbine system can be classified in a number of ways.

1. According to the rotational axis of the rotor

- Horizontal axis
- Vertical axis.

2. According to the size and capacity
   - Small wind turbine
   - Large wind turbine
3. According to their speed of rotation
   - Fixed speed wind turbine
   - Variable speed wind turbine

The horizontal axis wind turbine (whose rotational axis is parallel to the wind) is shown in Figure 2.1(a), and the vertical axis wind turbine (whose rotational axis is perpendicular to the wind) is shown in Figure 2.1(b) [60]. In addition, the wind turbine rotor can be propelled either by drag forces or by aerodynamic lift. The horizontal or vertical axis drag based designs operate with low speed and high torque, which can be useful mainly for grinding grains and pumping water. On the other hand, the horizontal and vertical axis lift based designs operate with high speed and low torque and are suitable for electricity generation. A wind turbine system can be classified as small or large depending on the rotor diameter, and capacity of generator. A typical configuration and design aspect of small and large wind turbines is shown in Table 2.1. The most useful classification in wind turbine industry is based on speed.

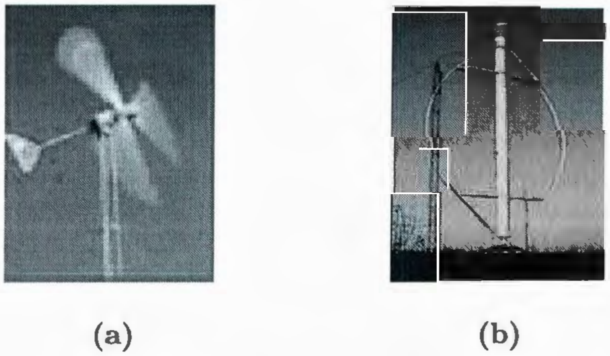


Figure 2.1: Horizontal and Vertical axis wind turbine

Table 2.1: Typical comparison of small and large wind turbines

Criteria	*Small*	*Large*
Power	0 ~ 100kW	660kW ~ 2MW+
Diameter	1~7m	10~100m
Hub height	~30m	~130m
Over speed control mechanism	Furling control, Flapping control, Passive pitching control, Load control	Pitch to stall, pitch to feather
Generator	DC Alternator, Permanent Magnet alternator, Induction generator[64]	Induction generator Synchronous generator
Application	Home, Farms, Remote application	Central station wind farm, Community wind

Wind turbines can operate with either fixed-speed or variable-speed. In a fixed-speed large wind turbine, the generator (induction generator) is directly connected to the grid. However, net-metering laws have currently been adopted in many parts of North America [65] that increases the public interest on small induction generator based grid connected wind energy conversion system [64]. One disadvantage of a fixed speed wind turbine is that the turbulence of the wind will result in power fluctuations, and thus affect the power quality of the grid [66]. In a variable-speed wind turbine, the generator is controlled by power electronic equipment, which makes it possible to control the rotor speed so that power fluctuations caused by wind variations can be more or less absorbed by changing the rotor speed [67]. However, controlling of variable-speed wind turbine is complex and increases the system cost compare to the higher production.

Small wind turbine systems can be tied to the grid or it can work isolated. One of the major issues of small WECS is to design a control system for monitoring the real situation for connecting/disconnecting the wind turbine system to the grid. As far as the concern of small grid connected wind turbine system, the output voltage fluctuations of the wind turbine system will not be affected due to the load flow changes. Due to the stochastic nature of the wind, wind gradient and tower shadow effect may contribute to inducing flicker in a grid connected wind turbine; however, the phenomenon requires attention, particularly in small wind turbine connected to the grid. A typical arrangement of a grid connected small wind energy conversion system shown in Figure 2.2 consists of a wind turbine, a generator, power electronic circuitry and a control system to maintain the grid connection/disconnection with the system at various conditions. A battery arrangement may be needed for a small grid connected wind energy conversion system to provide back up power for the instrumentation while grid is not available.

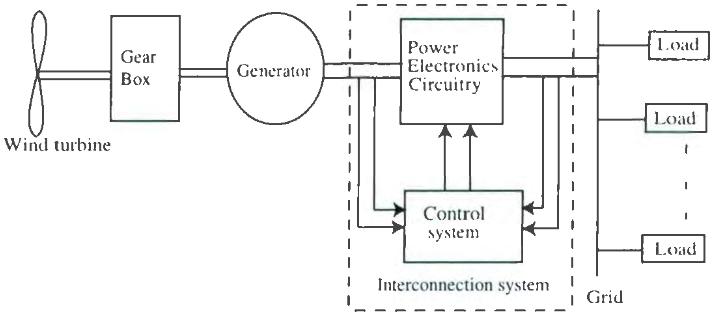


Figure 2.2: Small grid connected wind energy conversion system

2.3 Basic Outline of Wind Turbine Simulator

The generic configuration of a WTS evolves with a PC where the model and characteristics of the wind turbine are written either in high or low level language, a motor drive to represent the rotor of wind turbine, feedback mechanism from the drive and power electronics to control the drive. The drive is coupled with the generator which converts the mechanical energy produced by the wind turbine to the electrical energy. A typical configuration of a WTS is shown in Figure 2.3. The key part of feedback mechanism is data acquisition card. The feedback signal is generally acquired by a PC through analog to digital converter and the signal for driving the power electronics equipment comes from the PC through digital to analog converter. Literature search has shown that all the components in a WTS are similar except the selection of motor drives to simulate the wind turbine rotor. Different issues are considered for the use of an AC or a DC drives as wind turbine rotor in past. Before 1980, DC drives had significant advantages over other types of AC drives for adjustable speed drive application. Currently, AC drives are attracted due to the benefit of low cost and little or no maintenance in contrast to a DC drive. In addition, DC drive may be bulky and costly. However, speed or torque control of AC drive is more complex and requires expensive power electronics compare to DC drive. The other problem is that the AC drives are not suitable to operate below 1/3 of its base speed i.e., it will not properly reflect the actual wind turbine characteristics below 1/3 of its base speed. On the contrary, the DC drive is easy to understand and it has precise torque and speed control properties without sophisticated power electronics. Also in a DC motor, the torque and speed can be controlled directly by controlling the armature current and voltage respectively. It also nicely performs under variable speed cases. Moreover, the cost of the controlling equipment is lower than in the case of AC drives. The above explained reasons motivate this research to choose DC motor to reflect as the wind turbine rotor. The proposed wind turbine simulator provides the controllable wind turbine torque by controlling the speed of the DC motor. Most of the WTSs based on DC drive are controlled by the armature current [52], [56], [63] and few are controlled by armature voltage [48].

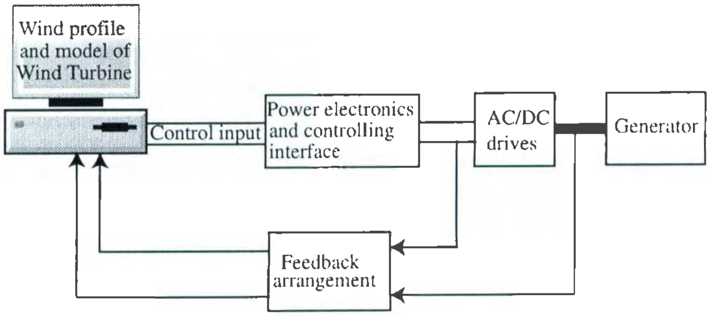


Figure 2.3: Basic outline of a wind turbine simulator

2.4 Proposed Wind Turbine Simulator

Wind turbine is a highly nonlinear system because of erratic nature of wind. In order to intensify the research and development on wind turbine system controls, it is important to better understand the steady state behavior of wind turbines.

In this thesis, a separately excited DC motor is simulated to reflect the characteristics of a 3 kW wind turbine. The DC motor is simulated as a fixed pitch horizontal axis wind turbine which follows the theoretical rotational torque of the wind turbine rotor. Inertia of the DC motor and induction generator is considered as the inertia of the wind turbine rotor. A PC based steady state wind turbine model is used in this research. Aerodynamic torque of the wind turbine is calculated from the rotational speed of the DC motor using wind turbine model equations which is considered as the reference torque of the WTS. The torque at the shaft of the DC motor is acquired by feedback mechanism. Based on the reference torque and the torque produced by the motor, the DC motor armature voltage is controlled via a phase control relay. A discrete PI controller is designed which makes sure that the actual rotational speed of the motor is same as that of wind turbine rotor. The basic outline of a small WTS proposed in this research is shown in Figure 2.4.

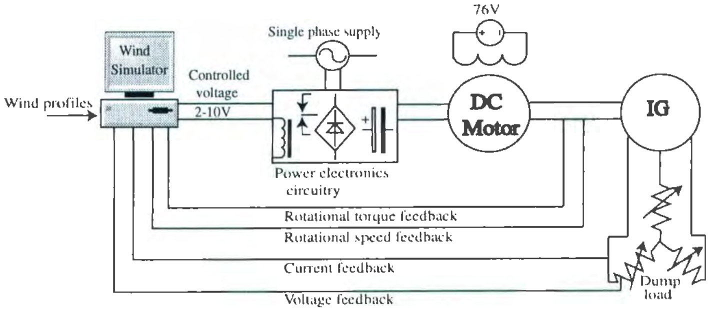


Figure 2.4: Proposed WTS representation

2.4.1 Modeling of Wind Turbine

In general, the wind turbine model defines the output characteristics of the wind turbine as well as its failure and repair processes [68]. Mathematical modeling of a wind turbine system is well understood and studied extensively [8], [9], [69], [70]. The model is developed based on the desired output characteristics. In this work, the desired output from the wind turbine model is torque and the wind turbine simulator, which is coupled with a self excited induction generator (SEIG) is designed.

The wind turbine is characterized by the non-dimensional curves of coefficient of performances such as (a) torque coefficient C_q, or (b) power coefficient C_p, as a function of tip speed ratio λ. The aerodynamic model of the wind turbine rotor in this research is based on the

C_q vs. λ curve. The C_q vs. λ curve is very useful in modeling of a wind turbine, because the wind turbine torque is not zero even if the rotor is at standstill [71].

The actual mechanical power at the output of the wind turbine rotor can be expressed as

$$P_{mech} = 0.5\rho A u_w^3 C_p(\lambda) \tag{2.1}$$

Where,

ρ = air density in kg/m^3

A = area swept out by the turbine blades in m^2

u_w =wind velocity in m/sec

$C_p(\lambda)$ = dimensionless power coefficient and is a function of tip speed ratio (λ). Tip speed ratio (λ) is the ratio of linear speed of the tip of blades to the rotational speed of wind turbine. It can be expressed as follows [72]

$$\lambda = \frac{\omega_m R_t}{u_w} \tag{2.2}$$

Where,

ω_m= angular velocity of the turbine rotor in rad/sec

R_t = radius of the rotating turbine in m

The average torque produced by the wind turbine is given by

$$T_{av} = \frac{P_{mech}}{\omega_m} \tag{2.3}$$

Combining equation (2.1) and (2.3),

$$T_{av} = \frac{0.5\rho A u_w^3 C_p(\lambda)}{\omega_m} \tag{2.4}$$

Substituting equation(2.2) into (2.4),

$$T_{av} = \frac{0.5\rho A u_w^2 C_p(\lambda) R_t}{\lambda} \tag{2.5}$$

or,

$$T_{av} = 0.5\rho A u_w^2 C_q(\lambda) R_t \tag{2.6}$$

Where,

C'_q = torque coefficient and can be expressed as the ratio of power coefficient and tip speed ratio i.e. $\frac{C_p(\lambda)}{\lambda}$.

The torque coefficient C_q vs. tip speed ratio λ curve is shown in Figure 2.5. The following equation characterizes the relationship between the torque coefficient and tip speed ratio.

$$C_q = -0.02812 + 0.038576\lambda - 0.0045912\lambda^2 + 0.0001489\lambda^3 \tag{2.7}$$

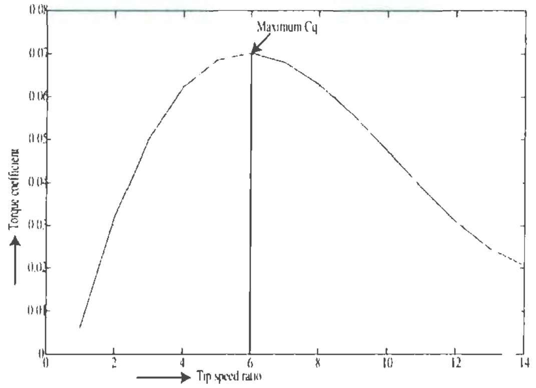


Figure 2.5: Torque coefficient versus tip speed ratio curve

2.4.2 Expected Rotor Torque for the Wind Turbine Simulator

The reference torque for the wind turbine simulator is defined by the above described wind turbine model equation. The gear ratio is used to obtain the wind turbine rotor speed from the speed of DC motor. The acquired wind turbine rotor speed is fed to the wind turbine model equation to calculate the theoretical torque of the wind turbine. From equation 2.6, the reference torque can be expressed as

$$T_{ref} = 0.5\rho A u_w^2 C_q(\lambda) R_t \tag{2.8}$$

2.4.3 Recursive Control Algorithm for the Wind Turbine Simulator

PI/PID controller is a well established and extensively used control algorithm for many applications because of ease of implementation and requires less computing power. However, the discrete form of the control algorithm is important for implementation in a PC. The time domain PID controller equation can be expressed as [73]

$$u(t) = K\left[e(t)+\frac{1}{T_I}\int_0^t e(\tau)d\tau + T_D\frac{de(t)}{dt}\right] \tag{2.9}$$

Where,

$u(t)$ = output of the controller at any instant t

$e(t)$ = error between expected and actual output

K = gain which is equal to proportional gain of the PID controller

T_I = Integration time of the controller

T_D = Derivative time of the controller

For small sampling time T_o, the above time domain controller equation can be converted to equivalent discrete form by approximating the integral and derivative term. The digitized form of PID controller equation can be written as

$$u(t) = K\left[e(k)+\frac{T_o}{T_I}\sum_{i=0}^{k} e(i-1) + \frac{T_D}{T_o}(e(k) - e(k-1))\right] \tag{2.10}$$

Where,

k = discrete time step

$e(k-1)$ = error occurs in previous step

This is a non-recursive control algorithm. For the information of a sum, all past errors $e(k)$

have to be stored. This algorithm is called position algorithm. However, recursive algorithms are more suitable for programming on computers. Recursive algorithms are characterized by the calculation of the current manipulated variable $u(k)$ based on the previous manipulated variable $u(k-1)$ and correction terms. By considering the previous manipulated variable from k^{th} step, equation (2.10) can written as

$$u(k-1) = K\left[e(k-1) + \frac{T_o}{T_I}\sum_{i=0}^{k-1} e(i-1) + \frac{T_D}{T_o}(e(k) - e(k-1))\right] \tag{2.11}$$

Combining equation (2.10) and (2.11)

$$u(k) - u(k-1) = K\left[e(k) - e(k-1) + \frac{T_o}{T_I}e(k-1) + \frac{T_D}{T_o}(e(k) - 2e(k-1) - e(k-2))\right] \tag{2.12}$$

or,

$$u(k) - u(k-1) = p_0 e(k) + p_1 e(k-1) + p_2 e(k-2) \tag{2.13}$$

$$p_0 = K(1 + \frac{T_D}{T_o}) \tag{2.14}$$

$$p_1 = K(\frac{T_o}{T_I} - 2\frac{T_D}{T_o} - 1) \tag{2.15}$$

$$p_2 = K\frac{T_D}{T_o} \tag{2.16}$$

It can be noted from equation 2.13 that the current change in the control variable is calculated based on current manipulated variable and previous manipulated variable. This algorithm is called velocity algorithm. This algorithm has the following advantages over the positional algorithm.

- Suitable for computer aided design
- The previous control can be set to any reasonable arbitrary value which makes it easier to tune
- It has the anti integral wind up property because it never uses the summations of errors to calculate the contribution of the integral term

Selection of Controller

PI controller is chosen as the WTS controller because of its simplicity and the nature of the system. In PID controller, the derivative control gain might be affected by the noise from the electrical systems and interfacing circuitry. The PI controller has the ability to make the steady state error zero, easy to implement and tune. Therefore, the controller equation summarized in 2.13 can be rearranged by eliminating derivative term as follows.

$$u(k) - u(k-1) = p_0 e(k) + p_1 e(k-1) \tag{2.17}$$

or,

$$u(k) = u(k-1) + p_0 e(k) + p_1 e(k-1) \tag{2.18}$$

where,

$$p_0 = K \tag{2.19}$$

$$p_1 = K(\frac{T_o}{T_I} - 1) \tag{2.20}$$

2.4.4 Implementation of Wind Turbine Simulator

In order to implement the above described WTS, several issues are considered. To calculate the reference torque of the WTS, it is required to acquire the speed information of the DC motor shaft. The feedback mechanism is implemented using a miniLAB 1008 I/O card, and calibration equations for speed and torque sensors are determined. The miniLAB 1008 DAQ is an accurate, powerful, low-cost, USB-based data acquisition instrument featuring 8 single-ended or 4 differential 12-bit analog inputs, two 10-bit analog outputs, 32 total DIO bits (4 through screw terminals, 28 through a connector), and an event counter. Basically, the feedback signal is acquired by the PC through analog-to-digital converter and the signal for driving the power electronic circuitry comes from the PC through digital-to-analog converter. Amplifier and filter are used in conjunction with the current and voltage sensors. The controller output triggers the phase-controlled relay to obtain the controlled variable DC voltage for the DC motor. A bridge rectifier is used to rectify the output of phase controlled relay.

Instrumentation for Wind Turbine Simulator

Figure 2.6 shows the instrumentation of the developed WTS. The field of DC motor is excited by a single phase supply using a bridge rectifier and a series power resistor. The output of the speed sensor is an AC signal which passes through RMS to DC converter. The DC output is then passed through a differential amplifier. The output of the differential amplifier is acquired by the PC using Minilab 1008 I/O analogue to digital converter. A calibration equation between speed and corresponding voltage at the sensor output is determined and used in PC to obtain the rotational speed of the DC motor shaft. Torque sensor output is fed to a high gain instrumentation amplifier because of low output of the sensor. The output voltage is then sent to PC through analogue to digital converter. The PC sends a control signal through digital to analogue channel of the I/O card to trigger the phase control relay. Output of the phase control relay is then passed through a bridge rectifier and applied across the armature of the DC motor. The armature control voltage is passed through a fuse to avoid unexpected situations. Required power supply for the instrumentation is obtained using a power supply unit. The photograph of the WTS instrumentation is shown in Figure 2.7.

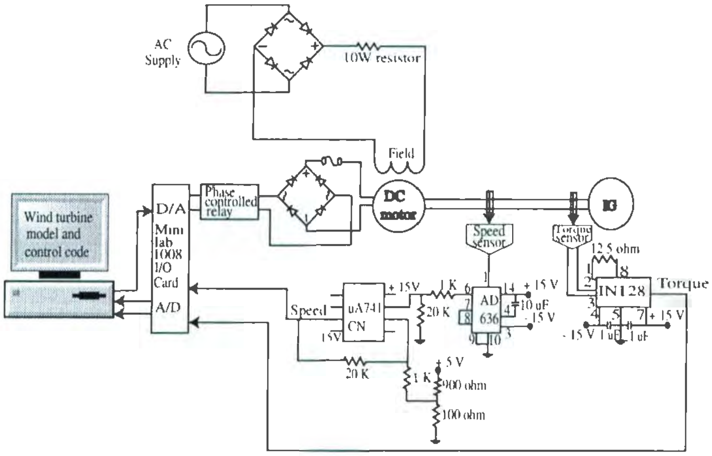


Figure 2.6: Wind turbine simulator instrumentation

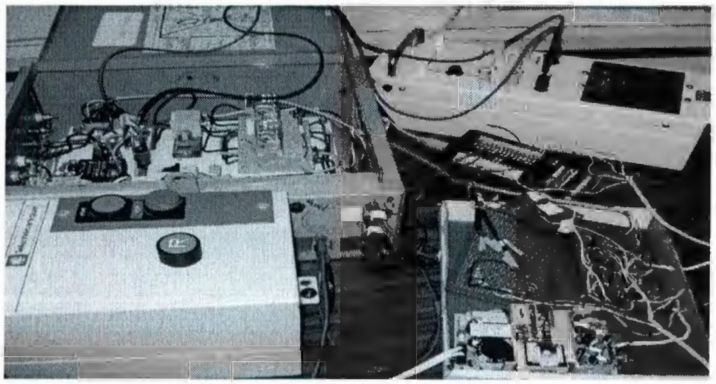


Figure 2.7: Photograph of the wind turbine simulator instrumentation

Calibration Equations for Interfacing

Acquiring speed and torque information from the DC motor was done using sensors, interfacing I/O card and electronic circuitry. The output of each sensor was in voltage. Therefore, voltage corresponding speed and torque values were obtained using calibration equations.

A speed sensor was connected to the shaft of the DC motor to generate a voltage corresponding to the rotational speed. The output voltage of the speed sensor was sent to analogue channel of the ADC which takes the bipolar 10V as its input. Therefore, calibration equation was determined so that the full range speed (0-2900 RPM) of the DC motor represents the bipolar 10V. Several input voltages for the armature were sent from PC and corresponding speed was recorded. A curve fitting technique was used in MATLAB to obtain the calibration equation. The actual data and the approximate model are shown in 2.8, and the calibrated equation was

$$\text{Rotational Speed} = (154.17 \times V_s) + 1358.3 \text{ rev/min} \tag{2.21}$$

A torque sensor was attached to the shaft of the DC motor. The calibration equation between the output voltage of the torque sensor and the torque at the DC motor shaft was given into [74]. The calibration equation was

$$\text{Torque} = (V_{TS} - 0.28) \times 1.4546 \tag{2.22}$$

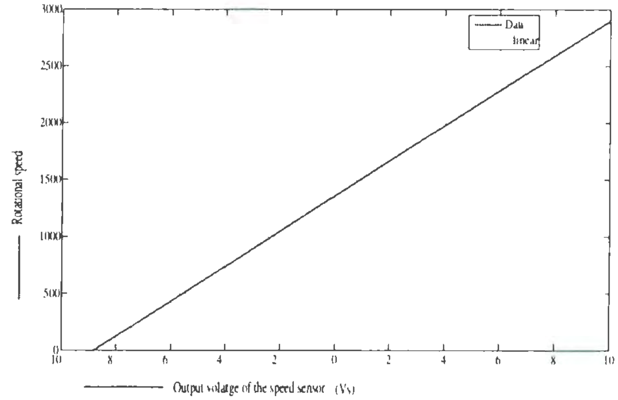


Figure 2.8: Rotational speed vs. output voltage of the speed sensor

Where,

V_{TS} = Torque sensor output voltage

Tuning Method of the Controller

Controller tuning is the way of selecting the controller parameters to meet given performance specifications. A well known Ziegler-Nichol's (ZN) closed loop tuning method is chosen in this research because the output of the system exhibits sustained oscillations for whatever value of the proportional controller. A closed-loop system is also able to regulate itself in the presence of disturbance or variations in its own characteristics. The following steps are taken while tuning controller using ZN method [73]:

- start controller with a low gain
- gradually increase the gain, until the oscillations start
- adjust the gain to make the oscillations continue with a constant amplitude
- Record the gain (ultimate gain, K_u) and period (ultimate period, P_u). The gain at which the oscillations continue with constant amplitude is called ultimate gain

The above described tuning method is done experimentally and calculated the ultimate gain and period. The Table 2.2 and the calculated ultimate gain and period are used to obtain

Table 2.2: Ziegler-Nichols tuning rule based on ultimate gain and ultimate period

Controller	K	T_I	T_D
PI	$0.45K_u$	$\frac{P_u}{1.2}$	0

the preliminary guess value of the PI controller. Flow chart of the PI control algorithm to simulate the DC motor is shown in Figure 2.9.

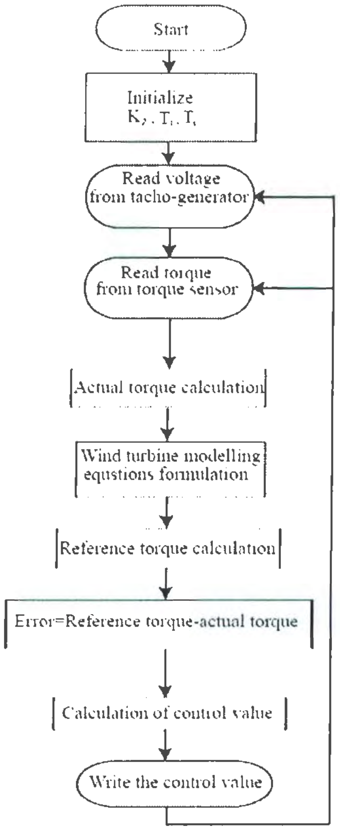


Figure 2.9: Flow diagram of the implemented control algorithm

Flow Diagram of WTS Control

At a glance, the above described wind turbine simulator can be represented in a flow chart. Flow diagram explanation for the proposed WTS is implemented in PC using VISUAL BASIC (VB) 5.00 is shown in Figure 2.10. In VB, a command prompt window (shown in appendix A) provides all information, while the entire code executes under that window. Initialization is an important for developing computer algorithm. The controller parameters with sampling time and wind turbine constants are initialized at the very beginning. The output of the tacho generator and torque sensor was feedback via ADC channels of the USB I/O card. Two analogue channels of the I/O card are used to acquire these voltages. Calibration equations were determined and set into the program which is used to calculate the actual speed and torque information. Speed of the DC motor, and wind speed from a file were used to calculate the tip speed ratio which is fed to equation 2.5 to calculate the torque coefficient. After calculating torque coefficient, reference torque is determined using equation 2.8. The difference between the reference torque and the feedback torque was then sent to PI controller. The PI controller tried to minimize the error and sent the control value via DAC channel of the USB I/O card to trigger the phase control relay. The rectified output of the phase control relay is then applied to the armature of the DC motor. The sampling time of the controller is determined by observing the total time to execute the loop. The input to the program was provided from a wind data file and the output was also recorded in a file. As the digital to analogue channels of USB I/O card only take 0-10V as its input, a voltage limiter was introduced in the program to obtain the final control variable within that limit. The details programming code implemented for WTS is given in appendix A.

2.5 Wind Turbine Simulator Test Results

The proposed WTS is implemented and tested in the energy systems lab at Memorial University of Newfoundland. In this test, a fixed pitch horizontal-axis turbine has been programmed in the WTS and it is coupled to a self excited four pole IG. This type of generator is particularly appropriate for grid connected operation, because they generate constant frequency and voltage, while operating over a small rotational speed range. A discrete PI controller has been designed that controls the DC motor in such a way that its shaft behaves as a wind turbine rotor and provides a controllable torque. The control code was implemented in VISUAL BASIC 5.00 and the starting inrush in the armature current of the DC motor was controlled by programming which reduces the need of any extra circuitry. The performance of the WTS was tested using constant and step change in wind speed, and variable speed wind profile.

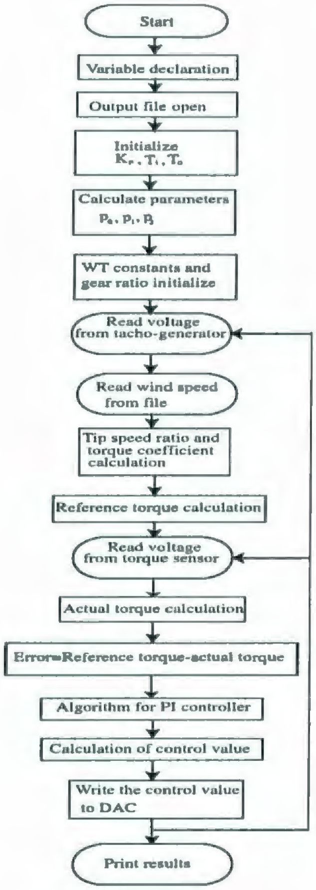


Figure 2.10: Flow diagram for the developed WTS control code

2.5.1 Results for Constant and Step change in Wind Speed

To reflect the wind turbine characteristics is the main challenge for developing and testing WTS in the laboratory environment. Practically, wind turbine starts to rotate and produces power at the shaft, whenever wind flows through a rotor plane and as long as the flow remains. The flow may be either constant or suddenly changed. So a developed WTS should be able to follow the theoretical torque of the rotor for a specific wind speed or a sudden change in the wind speed. To examine this performance, a constant and a sudden change in the wind speed profile was fed to the wind turbine model. The test result for a constant and a sudden change in the wind speed profile is shown in Figure 2.11. For t=0 to 300 seconds, a constant wind speed 7 m/s was fed to the model and a step change in the wind speed is occurred at t = 300 seconds. In Figure 2.11, the upper trace implies the reference torque produced

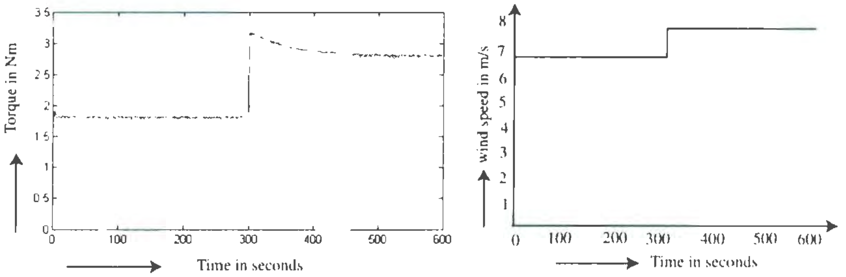


Figure 2.11: Reference and actual torque for constant wind speed (7 m/s) and a step change from 7 m/s to 8 m/s.

by the wind turbine model and lower trace indicates the actual torque of the simulator. In both cases, either a constant speed or a step change in speed, the actual torque reached the corresponding reference value by 2 minutes. The settling time is higher because of the inertia of the DC motor and the generator. The figure 2.11 also shows the step change in wind speed that was fed to the wind turbine model.

2.5.2 Results for Variable Wind Speed Profile

Due to the erratic nature of wind, another test was carried out by feeding variable wind speed profile to evaluate the WTS performance. This test is more significant to reflect the wind

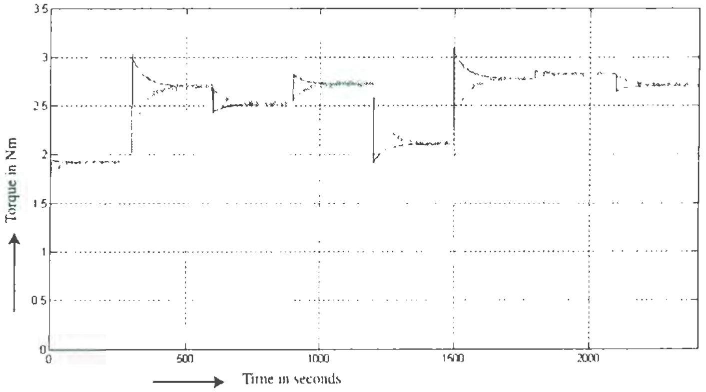


Figure 2.12: Simulated torque output with the variation in the wind speed

turbine characteristics properly into the developed WTS while wind speed varies randomly. Variable wind speed was given as the input to the wind turbine model results in higher/lower reference torque. Figure 2.12 shows the actual torque and corresponding reference torque

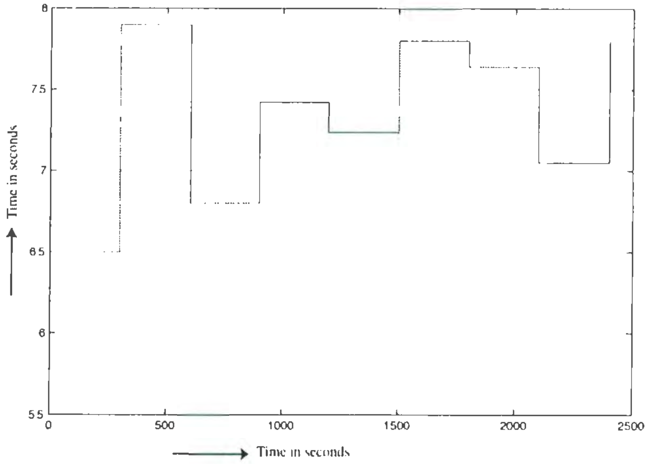


Figure 2.13: Variation in the wind speed profile fed to the wind turbine model during WTS testing

produced by the turbine shaft for the variation in wind speed. The DC motor actual torque is about same as the reference torque after two minutes of the wind speed change. The change in the wind speed was every 5 minutes. Figure 2.13 shows the variation in the wind speed that was fed to the wind turbine model. A discrete PI controller was designed that controls the DC motor in such a way that its shaft behaves as a wind turbine rotor and provides a controllable torque. A ZN closed loop tuning method described in section (Tuning method of the controller) is used to obtain the primary guess about the value of controller parameters. After some trial and error the best parameter values of the controller was found.

2.6 Summary

Design, development and test results of a WTS are presented in this chapter. Simulation of DC motor as a wind turbine rotor is performed by designing a discrete PI controller. The developed WTS produces the steady-state characteristics of a given wind turbine at various wind conditions. The performances of the wind turbine simulator are investigated using a constant wind speed, a step change in the wind speed and a variable wind speed profile. The experimental results prove the ability of WTS to vary the DC motor torque same as wind turbine rotor would do.

Chapter 3

Control Modes and System Instrumentations

In the past few years, increased penetration of wind energy into electrical power systems has made the latter dependent on the wind energy production. In addition, future wind turbines must be able to replace conventional power stations, and thus be active and controllable elements in the power supply network [39]. Obviously, interaction of wind turbines with electrical power-grids is becoming more significant. Therefore, it is important to develop control system in order to investigate all the aspects related to the interaction between wind turbines and the power grid both during normal operation and during grid faults. Currently, small grid connected wind turbine system is becoming very attractive due to net-metering laws. Control system for small grid connected wind turbine is also important to maintain the grid interaction with the system in different conditions. Reliable operation of the control system is required to operate at different modes of operation. The objective of this chapter is to show the construction of the controller that has the capability to operate at different modes of operations. This chapter also shows the system instrumentation in details for the measurements of the system parameters.

3.1 Introduction

During the past, several controllers have been developed to operate small grid connected wind turbines. Such a controller is important for the turbine to operate safely and also to supply clean power into the grid. The system controllers are used for small grid connected wind turbines have already discussed in system controller section. Controller designed by ENERTECH company connects the ENERTECH wind turbine to the grid only when the induction motor is working as a generator, and disconnects when it works as a motorized fan [15]. The controller designed by ENERTECH only operates in grid connected mode and there is no clarification about the controller operation while grid is absent. System controller designed by "SMA Technologie" for small wind energy converter "aerosmart5" controls the system operation [16]. The wind energy converter is controlled and connected to the grid by means of a specially developed microprocessor system, with the control unit responsible for generator switch over, braking, grid interconnection and booster loads. System capability for decentralize applications is achieved through parallel operation with SMA's "Sunny Island" battery power converter which controls voltage as well as frequency and rotational speed depending on its configuration. A 20 kW Gazelle wind turbine is commercialized by Gazelle Wind Turbines Ltd [17]. The control of this wind turbine is done using a PLC which can operate both in grid connected and stand-alone mode. Such an arrangement is not suitable for small low cost wind turbine due to the high cost of PLC. In addition, the above discussed controllers are for 5kW or more rated wind turbine system. ENDURANCE Wind Turbines is currently testing a prototype of a 3.75 kW induction generator based wind turbine which is expected to be available at the market by the end of 2007 (www.windwardengineering.com/Endurance). Details of its control system are still unknown. Therefore, an extended research and investigations are still required to design controller for 3kW or less rated wind turbines. Moreover, some of the above described controllers do not mention about the controller operation in grid unavailability while wind is enough to producing power. In this research a cost effective micro-controller based control system is proposed for small induction generator based wind turbine. Such a controller can operate the system in two different modes which increases the system efficiency. (a) Availability of wind with grid, and (b) availability of wind without grid are categorized as two main modes of operation for the controller. The system controller operates in two modes based on the measurement of voltages, speed, frequencies, power, and current flow between the generator and the grid. A low cost and reliable measuring circuitry is designed to determine the system parameters. Low cost is very significant for small system and reliability for the measuring unit is also required for avoiding unexpected operation of the controller. In a simplest option it can operate the wind turbine only on the power measurement basis. This chapter describes the control modes of the proposed micro-controller based system controller and the design of low cost parameters measuring instrumentations and installation issues for grid interaction.

3.2 Choice of Wind Power Converter

Literature search indicates that a number of wind turbines are designed based on permanent magnet generator or field regulated alternators. A very common application of such wind turbines is battery charging and they are primarily designed for stand alone applications. Such wind turbines may be connected to the grid using commercially available grid tie inverters, in combination with a charge controller, a battery bank and dump load. However, this idea is not cost effective mainly due to the associated costly power electronics, batteries and additional maintenance requirement of the battery bank [64]. An IG based wind turbine that meets all the requirements of the IEEE 1547 standard would be the better option for households. Several basic principles of generating electricity with wind energy and induction machines could be considered [75]. Firstly, adjustable speed wind generators which are very common in the modern wind energy conversion system because it provides low mechanical stress on all parts of the wind turbine, reduced power fluctuations in the grid, improved system efficiency and reduced noise emission in all weather conditions. Secondly, doubly fed induction machine is becoming more common in wind power generation. Currently, 70% of the commercial wind turbines are equipped with doubly fed induction machines. This kind of wind power generating system reduces the converter cost compared to the full inline converter since it is rated for only 30% of the total power of the generator. Moreover it also reduces the cost of emc-filter due to the lower power consumption. Although the doubly fed induction-generators have considerably greater speed variation for optimum efficiency [76], such systems require a complex control methodology as it is operated in variable wind speed. On the other hand, a squirrel cage induction machine with a gear box could be directly coupled with the grid that is operated at fixed wind speed. The major benefit of this concept is simple construction of the wind turbine system with very low investment and maintenance costs. Power converter is not required which reduces the system cost and increases the conversion efficiency for this system. The first two strategies are not suitable for small wind turbine system because of system complexity and cost issues. Therefore, this research has focused on a fixed speed self-excited induction generator based wind turbine system which is rated at 3 kW. Squirrel-cage induction machines (either generators or motors) have rugged construction; these are simple, reliable, cheap, and require minimum maintenance [77], [12], [78]. Furthermore, self excited induction generator can perform well under a small increase in speed from their rated value due to saturation and also due to the nonlinear relation between the rate of increase of the generated voltage and the speed [79]. In addition, it has the self protection mechanism because the voltage collapse when there is a short circuit at its terminals [79].

3.3 Control Modes

The performance of the controller depends on its operational mode i.e. the issues covered by the controller operation. Control for a wind power generating system can be considered as the machine control and the system control. System controller of a small wind turbine system should also take care while grid is off but the wind turbine is producing power. Thus some new challenges in designing controller of such a system are the connection/disconnection to the power grid, reasonable voltage regulation during off grid operation, and autonomous operations under grid failure. The entire operation of the control system is divided into two major modes.

1. Grid-connected mode

2. Off-grid mode

3.3.1 Grid-connected mode

In grid connected control mode, basically all the available power that can be extracted from the wind is transferred to the grid. This mode depends on the availability of the wind and the grid. The structure of grid connected control mode is shown in Figure 3.1 which consists of wind turbine, gear box, self-excited induction generator, controller, and soft-starter. The wind availability can be classified as (a) low wind speed, (b) wind that can produce power at the grid voltage and frequency, (c) wind speed beyond the rated value, and (d) too high wind speed. According to the output power curve of a typical wind turbine, generator does not produce power if the wind is either less than the cut-in speed or more than the cut-off speed. At low wind speed which is more than cut-in speed but less than the speed need to produce power at the grid voltage and frequency, the generator produces power with the lower voltage and frequency than the grid is needed. Wind speed is such that the generator produces power at the more or less same voltage and frequency of the grid. At wind speed beyond the rated speed, the output voltage and frequency of the wind power generating system is higher than that of the grid. To control the output voltage and frequency of the wind turbine system at this situation, aerodynamic control is essential which has not been considered in this research. At very high wind speed, it is more important to safe operation of the wind turbine rather than generating power. Such a situation could be maintained using electromagnetic safety brake or electronically operated hydraulic brake which is assumed for this research. The other issue for grid connected mode is the availability of the grid which may be either a weak or a strong grid.

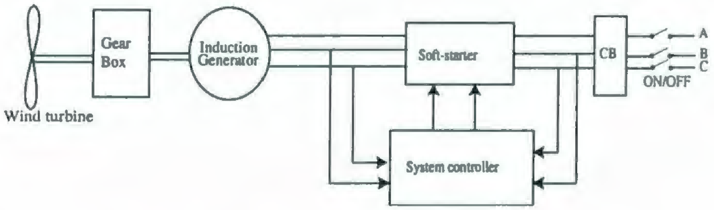


Figure 3.1: Grid-connected control mode

In this mode, the system controller functions while wind is low and enough to produce power at the grid voltage and frequency with the presence of grid. The controller can also function while wind speed is beyond the rated speed if the system is designed with the aerodynamic control. The system controller always monitors the generator terminal voltage and frequency, as well as the grid voltage and frequency at the available wind speed. While the generator and the grid parameters are matched, the system controller connects the generator to the grid via soft-starter. Once it is connected to the grid, the controller keeps checking current or power flow between the generator and the grid or the speed of the generator. Depending on one of these parameters the controller disconnects the system from the grid. Basically, the controller detects the generator operating mode that whether it is in motoring mode or in generating mode based on either current or power flow between the wind turbine system and the grid, or the speed of the generator. The control strategy is implemented on a development platform consisting of a wind turbine simulator based on a peripheral interface micro-controller.

3.3.2 Off-grid Mode Design

In off-grid control mode, the power generated by the wind power generating system needs to be transferred to the consumer load and the output voltages also need to be controlled in terms of amplitude. This control mode is defined by the uncertainty of the grid while wind is available to produce power. Grid uncertainty occurs when grid does not exist. The structure of the off-grid control mode is shown in figure 3.2 and it consists of wind power generator, system controller, soft-starter, phase control relay based electronic PI controller to regulate the voltage at the dump load terminal and the dump load. In this mode, the system controller and the phase control relay based electronic PI controller work simultaneously. The system controller performs both in grid-connected mode and off-grid mode whereas electronic PI controller works only in off-grid mode. Suppose wind turbine is generating power and after checking the system parameters, the system controller connects the generator to the grid via power resistor based soft-starter. Once it is connected to the grid, the controller

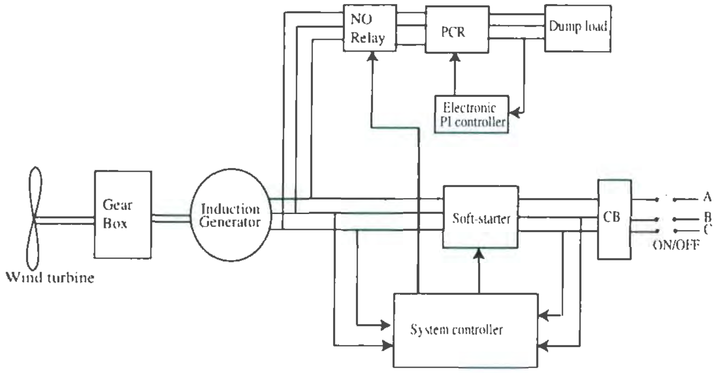


Figure 3.2: Off-grid control mode

keeps monitoring the voltages at the grid side and either power or current flow between the generator and the grid. In case of the grid failure or in off-grid situations, the grid voltage read by the system controller is zero. Once the system controller receives zero voltage from the grid side, the controller disconnects the wind power generating system from the grid and sends a control value to the normally open solid state relay to connect the system to a dump load. After connecting the dump load, electronic PI controller regulates the amplitude of the voltage at the dump load terminal. Wind availability needs to be considered while electronic voltage regulator is working. At this stage the system controller keeps checking the generator terminal voltage, frequency and also the grid availability. While the generator terminal voltage is too low due to the lack of wind, the system controller will send a control value to the relay placed between the generator and dump load to disconnect the generating system from dump load otherwise keeps the system connected to the dump load. The relay used for this purpose is normally open solid state relay. While the grid is recovered, the system controller again checks the synchronizing conditions. If conditions are met, the system controller disconnects the wind turbine system from the dump load and connects to the grid. Phase control relay based electronic controller is chosen for voltage regulation because of ease of implementation. A single control value can control the three phase control relays used in three different phases. This control strategy also keeps the wind turbine system free from islanding situation. Islanding of a grid connected wind turbine generator system occurs when a section of the utility system containing such generator is disconnected from the main utility, but the generators still continue to energize the utility lines in the isolated section. Situation may occur in the proposed system while wind is enough to produce power but the grid is absent. The proposed controller has the ability to detect the grid failure and switch over the system operation in stand alone mode, hence islanding situation will never occur.

While the generator is connected to the grid, the instrumentations and micro-controller is powered by the grid voltage. In off-grid control mode the instrumentations and controller may be powered by the generator terminal voltage and a small battery backup system. When the wind is too low at this mode, the generator will not be generating voltage however the system instrumentation and controller still needed power to keep it active and monitor the system parameters. To resolve this issue, a small battery back up power supply unit is proposed and designed for this control mode.

3.4 System Instrumentation

A low cost instrumentation is designed for measuring the parameters of the small grid connected wind turbine system. Block diagrams of the proposed instrumentation is shown in Figure 3.3 and 3.4. The measurement system shown in Figure 3.3 consists of voltage sensors,

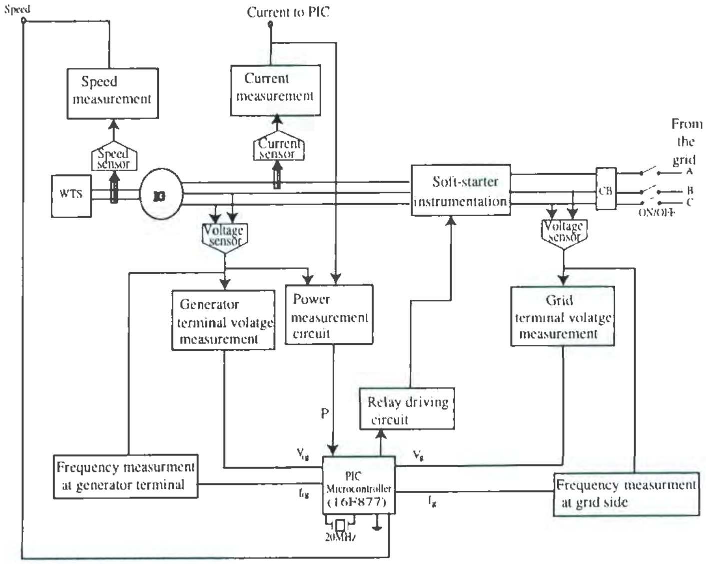


Figure 3.3: Block diagram of the system instrumentation during grid connected mode

current sensor, power measuring unit, frequency to voltage converter, soft-starter, and relay driving circuitry. Voltage sensors are placed both at the generator and grid sides. The current flow between the generator and grid is measured by using a miniature series current sensor. In power measuring unit, a four quadratic multiplier is attached in order to determine the power flow between the generator and grid. Voltage and current are the inputs to the multiplier which are acquired by voltage and current sensor. Frequency to voltage converter circuitry is designed to measure the frequency at both the generator terminal and the grid side. A power resistor based soft-starter is designed to achieve the soft connection between the generator and the grid. Soft-starter consists of three power resistors each in series with each line in combination with two relays. Transistors based relay driving circuit is designed to drive the relay of the soft-starter. A 10A protection circuit breaker (CB) is used in between soft-starter and grid. All measuring units are directly or indirectly connected to the PIC micro-controller. The measurement system shown in Figure 3.4 consists of a back up power supply unit for

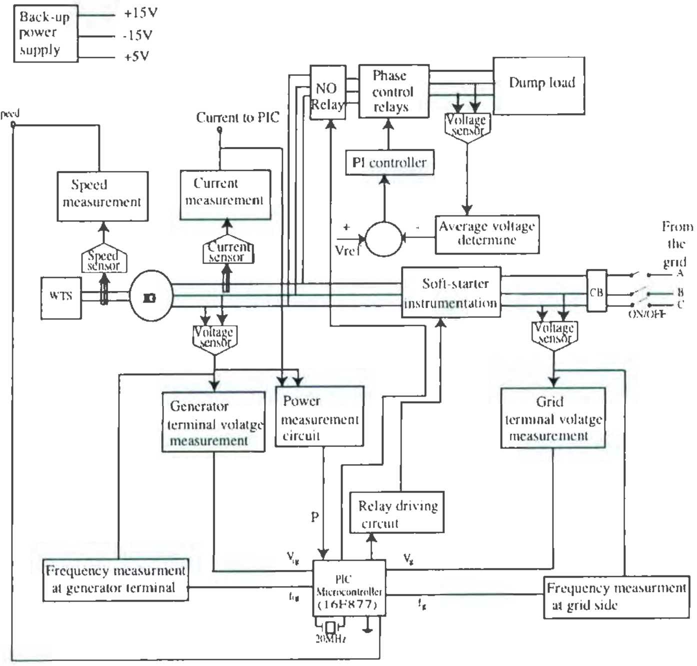
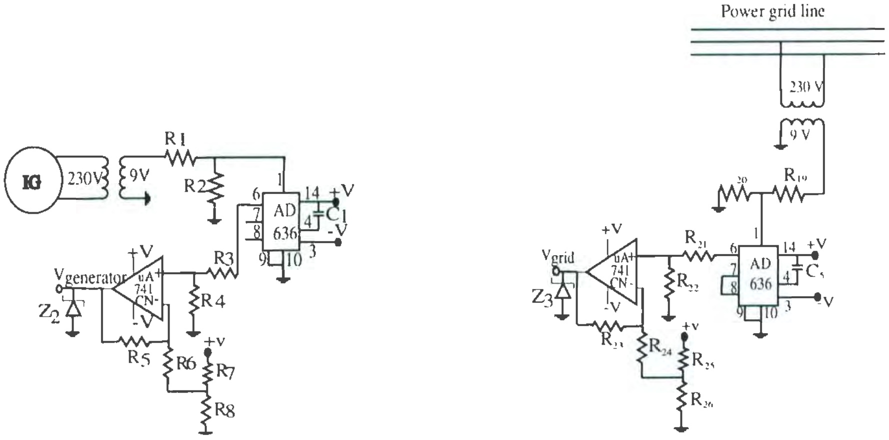


Figure 3.4: Block diagram of the system instrumentation for off-grid mode

off-grid control mode, an electronic PI controller based on phase control relay, a technique for acquiring feedback and reference signal for the PI controller, including the measuring units mentioned in Figure 3.3. The back up power supply provides power for the instrumentation circuitry and micro-controller while the wind is too low. An electronic controller is designed using operational amplifier which sends the control variable to the phase control relay. The phase control relay takes 2-10V DC at its input and provides the AC output voltage rated at 120/240V and 25A. The feedback mechanism is performed using voltage sensor, peak detector and low pass filter.

3.4.1 Voltage Measurements

Figure 3.5 (a) and (b) show the measuring circuitry of the generator terminal and grid side voltage in RMS value. Two voltage sensors are used to sense the generator and grid side voltages. EI type 230/9V transformers are used as the voltage sensor which is encapsulated, short circuit proof and has optimum price/performance ratio. Primary winding is connected between the two lines both at the generator terminal and grid sides. The output of the secondary winding of the voltage sensor is passed through a voltage divider to provide a small magnitude signal at the input of the root-mean-square (RMS) to DC converter. AD636 is used as a RMS to DC converter which is a low power and low cost monolithic IC. The AD636 computes the true RMS of a complex AC (or AC plus DC) input signal and gives an



(a) (b)

Figure 3.5: Voltage measurement at the generator and the grid terminal

equivalent DC output level. The true RMS value of a waveform is a more useful quantity than the average rectified value because it is a measure of the power in the signal. The output of the RMS to DC converter is then passed through a differential amplifier to amplify the small signal for better resolution in measurement. LM741 operational amplifier is chosen for amplification because it has overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

3.4.2 Frequency Measurements

Frequency is one of the important system parameters for grid interconnection. Measurement of frequency from generator and grid sides is performed using the developed instrumentation shown in Figure 3.6 and 3.7. VFC32 is used as a frequency to voltage converter in this research.

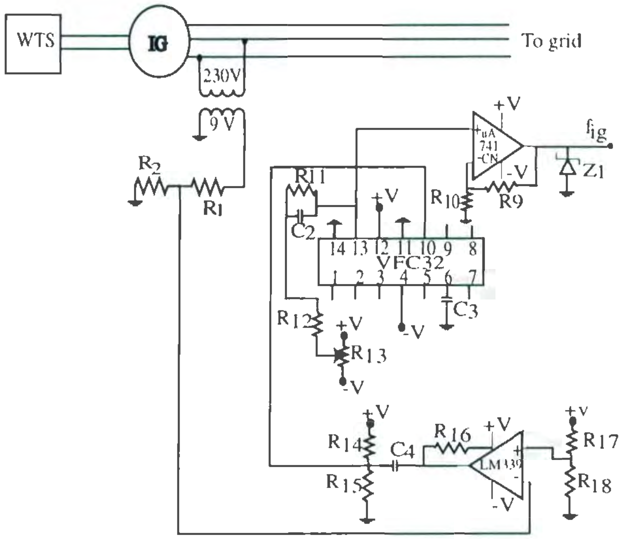


Figure 3.6: Instrumentation for measuring frequency at the generator terminal

The output of the voltage sensor is fed to the comparator to obtain logic level 0-5V of the acquired signal. The capacitive-coupled input network C_4, R_{14} and R_{15} in Figure 3.6 and C_6, R_{28} and R_{29} in Figure 3.7 allow standard 5V logic levels to trigger the comparator input of the VFC32. The comparator triggers the one-shot on the falling edge of the frequency input pulses. Threshold voltage of the comparator is approximately -0.7V. The value of C_3 and C_8 in Figure 3.6 and 3.7 respectively are chosen from the capacitor value selection characteristics curve given in data sheet according to the full-scale input frequency. C_2 and C_7 in Figure 3.6 and 3.7 smooth the output voltage waveform. Larger values of C_2 and C_7 reduce the ripple in the output voltage. Smaller values of C_2 and C_7 allow the output voltage to settle faster in response to a change in input frequency. Resistors R_{13} and R_{36} are used to be trimmed to achieve the desired output voltage at the full-scale input frequency. The output of the VFC32 is then amplified to keep it in 0-5V range for the micro-controller. A Zener diode is used at the output of the amplifier to limit the peak maximum voltage applied to the micro-controller in an unexpected situation.

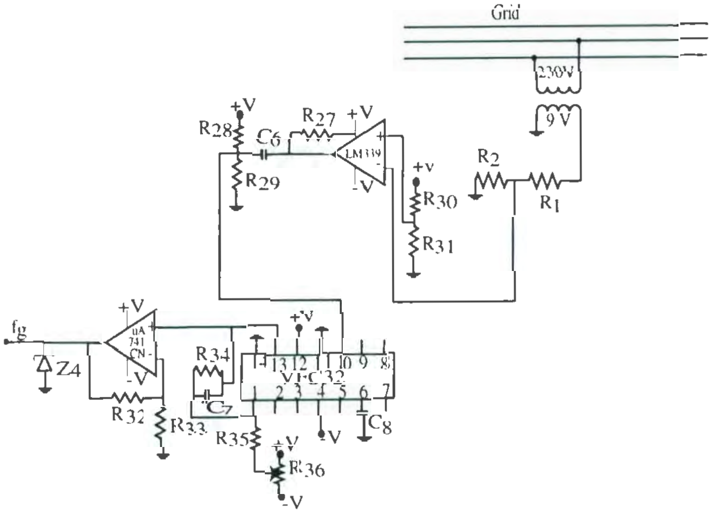


Figure 3.7: Instrumentation for measuring frequency at the grid side

3.4.3 Current Measurement

Measurement of current flowing between the generator and the grid is an important parameter for making decision to disconnect the system from the grid. The miniature MS-15 current sensor is used to measure AC current flowing between the wind turbine generating system and the grid. It also provides electrical isolation between the circuit being measured and the output. It is more useful because of operation in unipolar power source, small size and low cost. The output of the current sensor contains an AC signal with a DC component. The DC part of the signal is blocked by using a series capacitance and the AC component of the output of the current sensor is fed to the RMS to DC converter. The RMS to DC converter computes the true RMS value of the current flowing between the generator and the grid. The small DC signal coming out from the converter is then passed through a differential amplifier to obtain the signal in amplified form. The output of the current sensor is proportional to the current flowing through it. The instrumentation is shown in Figure 3.8.

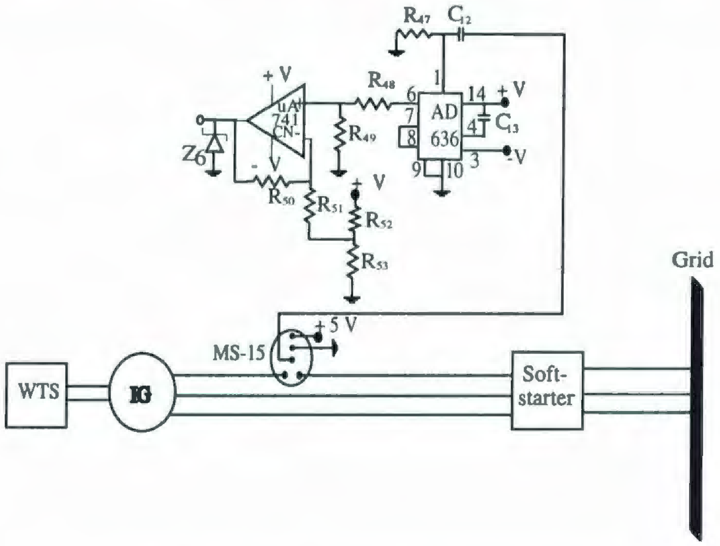


Figure 3.8: Current measuring instrumentation

3.4.4 Power Measurement

Disconnection decision from the grid based on power measurement is more suitable and accurate. The measured power identify the induction machine either it is operating in generator mode or in motoring mode. To obtain the power calculation, a four quadrant multiplier, a voltage sensor and a split-core current transformer are used. Voltage sensor is also used to measure the voltage in this case. A split-core current transformer (CT) is a low cost method to monitoring electrical current. A unique hinge and locking snap allows attachment without interrupting the current-carrying wire. The CT has high secondary turn which develops signals up to 10.0V AC across the burden resistor. The burden resistor used in the instrumentation is selected according to the electrical output characteristics of the CT. An analogue multiplier AD633 is used to achieve the multiplication of the two inputs. AD633 is a complete four-quadrant multiplier which is cost effective and easy to apply. There are no external components or expensive user calibration is required to use this multiplier. The output of the multiplier is then passed through a peak detector to obtain the average value of the calculated power and RC low pass filter to remove the high frequency noise generated from the circuitry. A Zener diode is also used at the final output to protect the PIC micro-controller from any unexpected events.

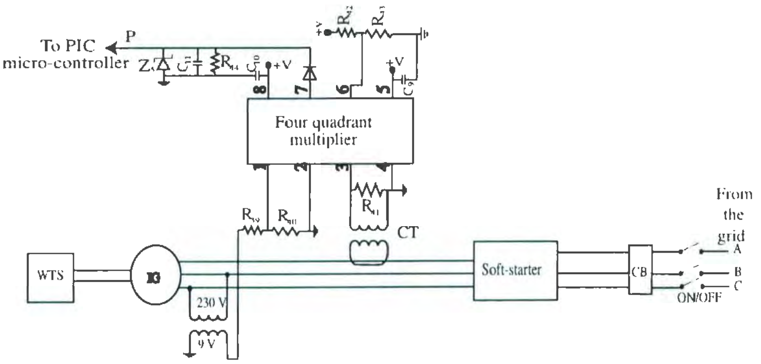


Figure 3.9: Power measuring circuitry

3.4.5 Speed Measurement

Speed is another parameter which is also considered for the system controller for disconnection decision. A tacho-generator is used that measures the voltage of the corresponding generator speed. The output is given by the tacho-generator is an AC signal which is passed through a voltage divider to obtain in an acceptable range of the true RMS to DC converter. AD636 is also used here as RMS to DC convert. The DC output of the AD636 is then fed to the differential amplifier to obtain the value in better resolution. A calibration equation is used in the controller algorithm which determines the actual speed of the generator by taking the voltage from the speed sensor.

3.4.6 Soft-starter Instrumentation

A power resistor based soft-starter strategy is proposed for small grid connected wind turbine. The soft-starter consists of three power resistor each of 6 ohm and 100W, two relays and relay

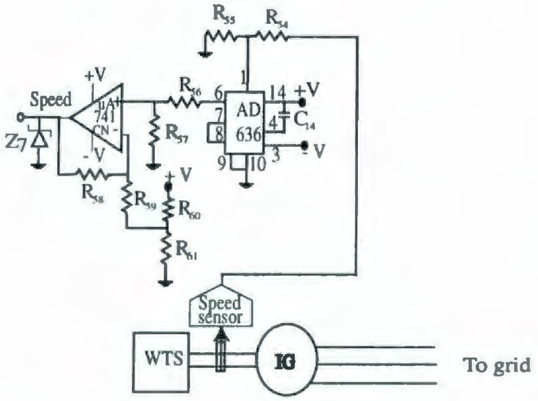


Figure 3.10: Measurement of generator speed

driver circuits. Soft-starter configuration is shown in Figure 3.11 and the driver circuit is shown in Figure 3.12. Three power resistors are connected in three contact points of *relay_1* which is shown in Figure 3.11. The *relay_2* is connected in between the induction generator and the grid as the main contact. Such type of soft-starter works first by connecting the system

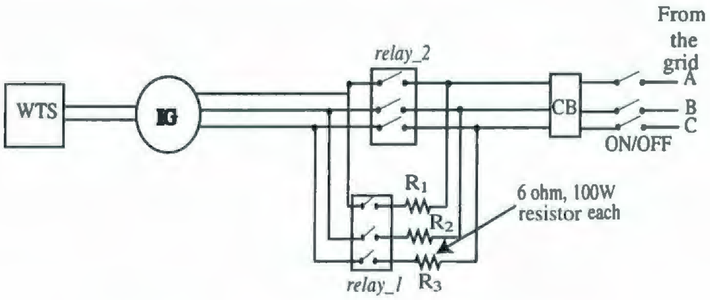


Figure 3.11: Soft-starter instrumentation

to the grid through power resistor using *relay_1* and after a suitable time the connection is set up by switching *relay_2*. Switching time delay between *relay_1* and *relay_2*, and the suitable values of the power resistors are determined through an experimental investigation. Relays are operating on 12V DC coil which are driven by the driver circuits. The driver circuits are simply based on PNP transistor where transistors are working as a switch. The transistors are activated by the control signal (logic 0-5V) coming from the system controller. Resistor R_{45} and R_{46} are used to limit the voltage applied across the relay coil.

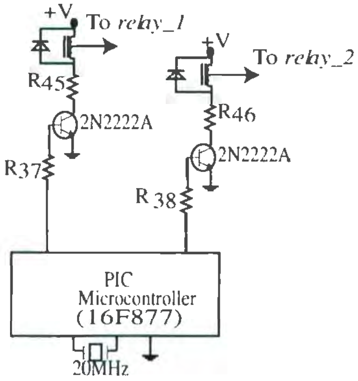


Figure 3.12: Soft-starter relays driver circuit

3.4.7 Voltage Regulation Instrumentation

Voltage regulation is necessary at the dump load terminal during off-grid control mode because of the randomly varying nature of the wind. An electronic PI controller is designed to control the amplitude of the voltage at the load terminal in combination with an analogue input power controller and a solid state relay. A fixed reference voltage is determined for the controller by observing the voltage at the secondary of the voltage transformer for maintaining the required voltage at the dump load terminal. To obtain the feedback voltage, the output of the secondary winding of the voltage transformer is passed through a peak detector. The average output voltage of the peak detector is then fed to a low pass filter to remove high frequency noise generated by the instrumentations and systems. The structure of the voltage regulation circuitry is shown in Figure 3.13. The PI controller block in Figure 3.11 basically contains the electronic proportional and integral controller which is designed using operational amplifiers. The output of the controller is then sent to the phase control relay to control the voltage at the load terminal. A normally open solid state relay is used in between the generator and the phase control relay to provide isolation between the dump load and the system, while the system operates in grid connected mode.

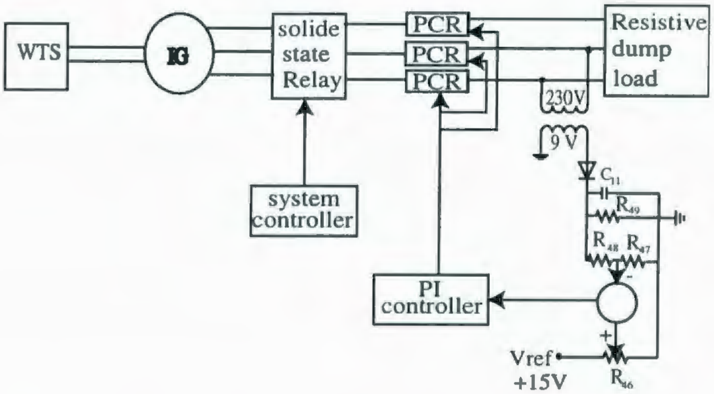


Figure 3.13: Instrumentation for voltage regulation at the load terminal

3.5 Back-up Power Supply Design

A back-up power supply unit is essential during the off-grid connection. The designed instrumentations and micro-controller takes power from the grid which is fine for the grid connection. However, at low wind during grid absent situation there will be no power to operate the instrumentations and micro-controller for continuous monitoring the system behavior. Therefore a small battery back-up power supply system is proposed in this research. The power supply system is shown in Figure 3.14 consists of battery charger, battery charge controller, battery, DC to AC converter. A 12V 6AHr lead acid battery is chosen for this system because a well maintained lead acid battery usually last longer than a sealed batteries. The lead acid battery charger is chosen to charge the battery to full scale and to maintain the capacity by compensating for self-discharge. To achieve the maximum battery capacity and life, a battery charge controller is selected in this design. Since the existing instrumentation is taken power from a power supply unit which takes input from a 120V AC supply, an inverter

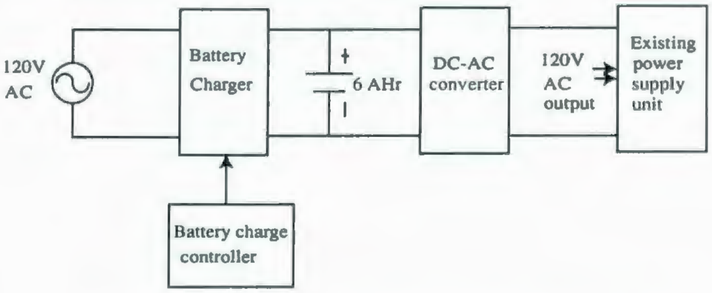


Figure 3.14: Back-up power supply system

is needed to convert the DC voltage stored in the battery to an AC voltage. However, due to the 10% loss of energy during the conversion process, this design may not appropriate for a small wind energy conversion system. Therefore, another alternate design of the back-up power supply unit for the system controller and the instrumentation is proposed. The basic components of such power supply unit is shown in figure 3.15 which consists of batteries, battery charger, voltage regulator integrated circuit (IC) and output capacitor.

Although the alternate back-up unit is less complex, it is needed six batteries and higher rated battery charger. Three batteries are connected to provide positive voltage and the other three are connected to provide negative voltage to the regulator IC. LM7815 and LM7805 are three terminal fixed positive output voltage regulator which are used to obtain +15V and +5V. LM7915 is also a three terminal negative voltage regulator which regulates fixed negative -15V. Those regulators are easy to use and minimize the number of external components in the design. The output capacitors are used at the output of the regulator ICs to improve the stability and transient response.

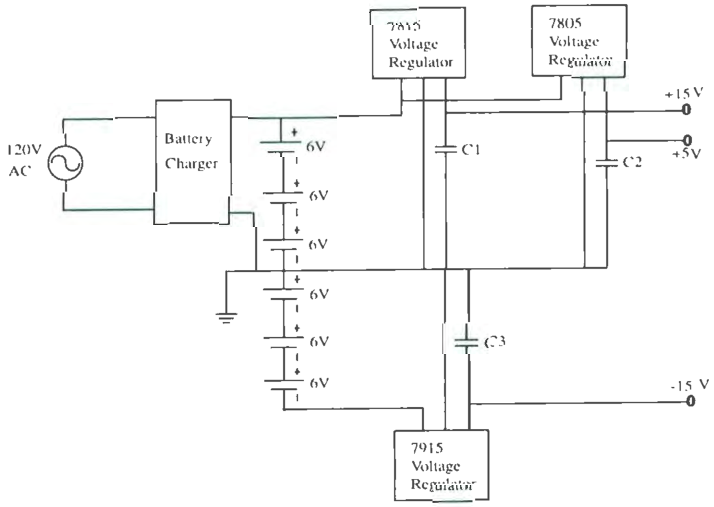


Figure 3.15: Alternate design of back-up power supply system

3.6 Installation Requirements

The system consists of hardware and software, which maintains connection between distributed resources (DR) unit and area electric power system (area EPS), is called interconnection system. DRs are the sources of electric power that are not directly connected to a bulk power transmission system. A typical configuration for connecting between DR unit and area EPS is shown in Figure 3.16. However, to connect the DR to the area EPS or power grid, and also to maintain the connection, there are some issues need to be addressed and maintained for strong grid connection are called installation requirements. The following general requirements have been set for the interconnection system by Standards Coordinating Committee 21 [80]. Table 3.1 shows the voltage requirements for small power generation system to connect to the grid. If the voltage at the point of common coupling (PCC) lies in a range mentioned in the table 3.1, a DR shall cease to energize the area EPS within the clearing time as mentioned. The clearing time mentioned in the table is the maximum clearing time for less or equal 30 kW DR unit. Table 3.2 shows the requirements for the frequency to connect and to maintain the connection between the power generation systems to the grid. If the frequency at the PCC lies in a range mentioned in the table 3.2, a DR shall cease to energize the area EPS within the clearing time as mentioned. The clearing time mentioned in the table is the maximum clearing time for less or equal 30 kW DR unit.

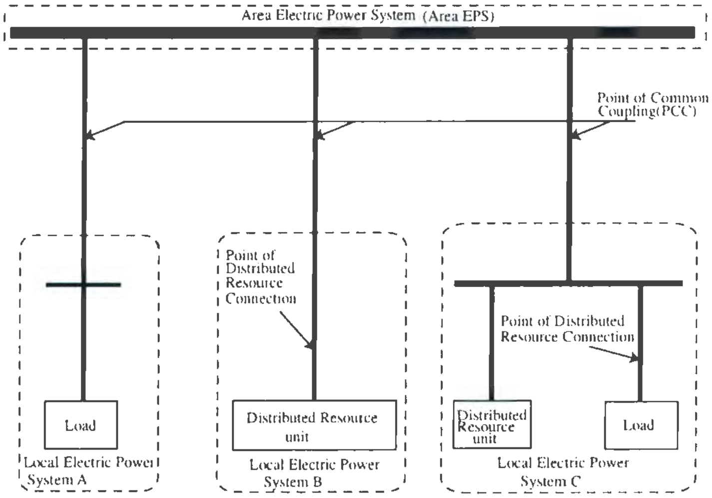


Figure 3.16: Connection arrangement between DR unit and area EPS

Table 3.1: Interconnection system response to abnormal voltages

Voltage range in percent of base voltage	*Clearing time in seconds*
$V<50$	0.16
$50\leq V<88$	2.00
$110<V<120$	1.00
$V>120$	1.00

Table 3.2: Interconnection system response to abnormal frequencies

Frequency range in Hz	*Clearing time in seconds*
Frequency > 60.5	0.16
Frequency < 59.3	0.16

Another issue called unintentional islanding is also needed to be considered during the installation. For an unintentional island in which DR energizes a portion of the area EPS through the PCC, the DR interconnection system should detect the island and cease to energize the area EPS within two seconds of the formation of an island.

3.7 Summary

Control modes of the proposed controller and the system instrumentation are described in this chapter. Two different modes of the system controller and the issues involved in the control system designed are also described. The schematics of the system parameters measuring circuits are presented in details. A power resistor based soft-starter design is also presented in this chapter. Voltage regulation at the dump load terminal and design of a back-up power supply unit for off-grid operation are presented. Finally, typical installation requirements for a grid connected system are described in terms of voltage, frequency and unintentional islanding.

Chapter 4

Control System Design and Implementation

This chapter presents design of a new, simple, and economical controller to connect/disconnect an induction generator based wind turbine from the grid under various conditions. The prototype controller has been developed using a PIC16F877 micro-controller which is programmed using Mikrobasic. This chapter also focuses on implementation of the design controller in different control modes using a developed wind turbine simulator.

4.1 Introduction

After the introduction of net-metering laws, a consumer can install small wind electric generation system at his/her premises and thereby utilize all the generated energy or can supply to the grid. It reduces the total cost although the cost/MW increases, making it an attractive investment for small investors. Therefore it is important to observe and investigate the system controller behavior in order for the system to provide reliability, quality power at the grid, and also to provide safe operation of the wind power generation system. In addition, design and implementation of a system controller for a small wind electric generation system should address several issues of practical application. The first implementation issue could be related to the aerodynamic behavior of the turbine blades which has already been discussed in chapter 2. The second important issue which is highly concentrated in this research is the system operational requirements. The operational requirements of a fixed speed grid connected wind turbine generation system includes automated grid connection/disconnection and maintenance of the connection. These situations may occur due to the level of wind power available and also due to the grid availability. In order to meet those operational requirements, it is necessary to control the system behavior in such way that the controller has the capacity to connect/disconnect the system from the grid under several stipulated conditions. A micro-controller based system is proposed which monitors and controls the system behavior at varying wind conditions. The system controller operates by measuring the system parameters such as generator speed, voltages and frequencies at the generator and grid sides, current and power flow between the generator and the grid rather than the sensing of wind speed by anemometer. Therefore the design challenges also include proper instrumentation to measure the control variables accurately and choice of low cost instrumentation to keep the total cost at a minimum level.

In addition, direct connection of the wind power generator to the grid results in high inrush current, which is undesirable particularly in the case of weak grids and can also cause severe torque pulsations and probably damage to the gearbox. To resolve this issue a power resistors based soft-starter is proposed for small wind energy conversion system. The power resistor based soft-starter is very simple, and control is not required unlike in semiconductor based soft-starter.

This research also considers the scenario when the grid is unavailable. When the grid becomes unavailable, the system should be able to produce power given that there are enough wind power available. In other words, the wind power system will act as a stand alone system to provide power to users. In such a situation, the system controller will monitor the generation system and grid status by checking their parameters. Once the system controller detects the grid is unavailable, the control will switch over to the off-grid mode. In the off-grid mode, the generation system is connected to a dummy load. However, due the variations in the wind speed, the terminal voltage at the dummy load also required to be regulated.

Voltage regulation at the dump load terminal is accomplished by a phase control relay based electronic proportional integral (PI) controller. While the system is operating in off-grid mode, the system controller also keeps checking the grid status. Once the grid is recovered, the system controller will disconnect the system from the dummy load and will return to the regular operational mode. However, during off-grid mode, the system controller and instrumentation require separate power supply. To meet this purpose, a small back up power supply unit is proposed.

Islanding is another technical issue which is necessary to consider for the small wind power generation system. Electrical system islanding occurs when the power grid is removed but wind turbines continue to operate and provide power to local loads. This issue is also overcome by the designed controller because the system will never connect to the grid while grid is absent. This chapter describes the implementation of the proposed controller and system instrumentation by addressing the above described issues.

4.2 Choice of the System Controller

For proposed implementation, there are several options available such as PC based control, PLC based control, a single board computer, and a micro-controller. Obviously, a PC and a PLC are not cost effective options for a low cost small wind turbine. The proposed controller requires a very low computing power and therefore a single board computer is unnecessary. A micro-controller with flash RAM is the cheapest and the most convenient to program as compared to all other options available. Therefore, a low cost PIC16F877 micro-controller has been selected to design the proposed controller. The PIC16F877 micro-controller is a low power, high performance RISC CPU 8-bit micro-controller with 8 kWords of flash programmable and erasable memory and 368 bytes of RAM (www.picbook.com). It has two 8-bit and one 16-bit timer/counters, two capture, comparators and pulse width modulation (PWM) modules, a full duplex serial port, parallel ports, an on-chip oscillator, a programmable code protection, 14 interrupt sources and a 10-bit 8 channel A/D converter. The micro-controller clock is generated by an external 20MHz crystal. Interface to the RS232 serial line is via a

MAX2020PE IC, which converts RS232 logic voltage levels to TTL levels accepted by the 877. In this research, PORTA is used as the analogue input channel and PORTB is used as the digital output channel. PORTA is a 8-bit wide, bi-directional port. The corresponding data direction register is TRISA. PORTA pin is defined as input by setting a TRISA bit (= 1). PORTB is also an 8-bit wide, bi-directional port and the corresponding data direction register is TRISB. PORTB is defined as output by clearing a TRISB bit (= 0). The ADCON0 register controls the operation of the analogue to digital converter (A/D) module. The analog input charges a sample and hold capacitor. The output of the sample and hold capacitor is the input into the converter. The converter then generates a digital result of this analog level via successive approximation. The A/D conversion of the analog input signal results in a corresponding 10-bit digital number. Mikrobasic is used for programming the PIC micro-controller in this research. The desired features for the system controller are:

- Control based on electrical measurements that avoids the use of wind speed sensor
- Grid connection through a soft-starter
- Over-voltage and under-voltage detection
- Abnormal frequency detection
- Monitoring and measurement of generator and grid voltages, frequencies, power and generator speed
- Disconnect the system from the grid within a few milliseconds
- Switch over the system operation in off-grid mode
- Islanding protection
- Identify the grid recovery and back the system connected to the grid

4.3 Controller Design for Grid Connected Mode

A block diagram representation of the designed control system during grid-connected operation mode is shown in Figure 4.1 which consists of WTS, self-excited induction generator, PIC micro-controller and system parameters measurement procedure. The control sequences for this mode can be expressed as follows. When wind speed is low, the generator disconnects from the grid as the rotating speed is low. As the wind speed increases, the generator speed and its output signal frequency also increases. The generator is not self excited yet, therefore it only produces a small voltage utilizing its remnant magnetism. The system controller senses the generator and grid voltages as well as frequencies. Excitation capacitors are connected across the generator and self excites above a certain rpm. When the generator reaches the self excitation, voltage is developed at the generator terminal. The generated voltage and frequency increases or decreases with the wind speed. The controller constantly monitors changes in the voltage and frequency at the generator terminal. The information about the voltages and frequencies are acquired by the measuring instrumentation as shown in Figure 4.2. The design of the measurement circuitry is explained in chapter 3. When the generator voltage and frequency reach the level of grid voltage and frequency, the controller sends a high signal D_0 to relay driver circuit, which operates the *relay_1* and the generator will be connected to the grid through a soft-starter. After 350 milliseconds, the controller turns on *relay_2* by sending a high signal D_1 (while D_0 low) and connects the system directly to the

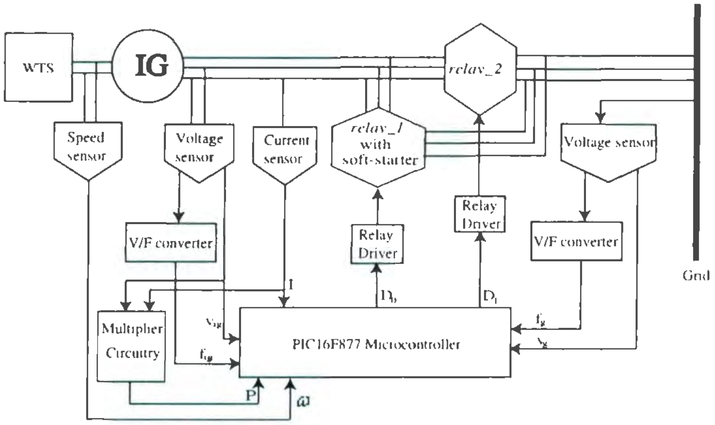


Figure 4.1: Block diagram representation of the system controller for grid connected mode

grid. Once it is connected to the grid, the controller monitors either the current or power flow between the generator and the grid, and the generator speed. Based on these measurements, the controller can take decision whether to 'maintain' or 'not maintain' the grid connection. Wind speed change is the cause to change the parameters upon which the disconnection decision is taken. Wind speed is such that the wind turbine system is delivering power to the utility grid. In this situation the current delivered by the generator to the grid is such that the generator is operating in or above the synchronous speed. If wind speed is low or less than the cut-in speed, then the generator terminal voltage will be low and the generator will draw current from the grid rather than deliver to the grid. In this case the speed of the wind power generator changes in a small range and goes below the synchronous speed, and at the same time the current flowing between the generator and the grid increases than the current at the synchronous speed. This logic is programmed in PIC micro-controller using Mikrobasic

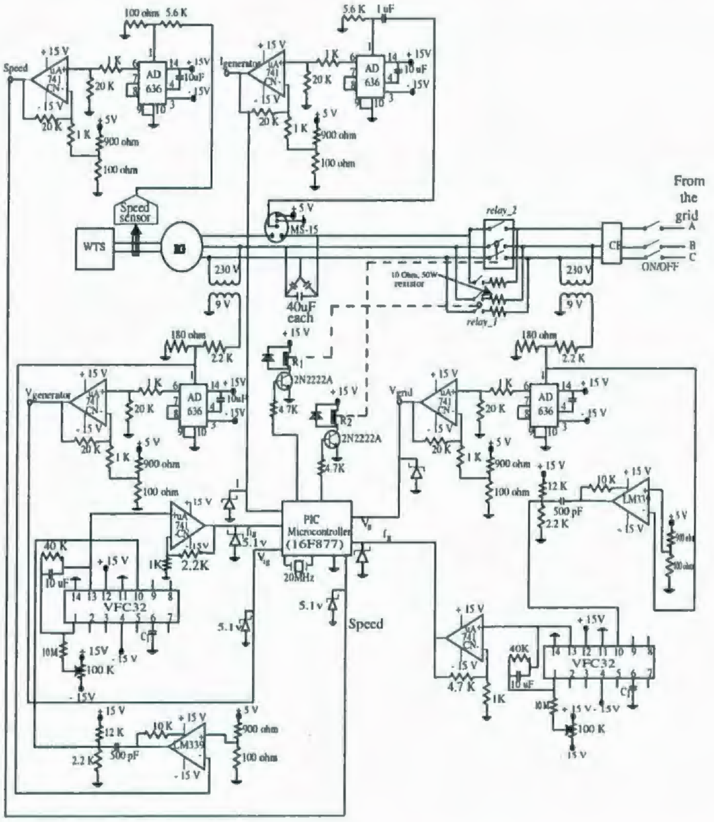


Figure 4.2: Schematic of the instrumentations for voltage, frequency and current measurements

and the parameters are measured using the instrumentation circuitry.

The disconnection decision from the grid can also be taken based on power measurement. A power measurement circuitry is developed using a four quadrant multiplier integrated circuit from which it is very easier to recognize the power is either positive or negative. An option is given in the multiplier to add a reference level which is accomplished by adding a DC value. If the power is positive while wind is strong then the output of the multiplier goes above the reference level. On the other hand if the power is negative while wind speed is low or less than the cut-in value the output of the multiplier goes below the reference level. This logic is programmed in the system controller which always checked the power status and taken decision for grid disconnection. If the controller disconnects the system from the grid due to the lack of wind, it will keep checking the terminal voltage and frequency at the generator terminal and the grid. When the grid connection condition is met due to strong wind, the controller will again connect the system to the grid. In other case, if wind is available to produce power however the grid is not available then the controller will switch over the system to off-grid control mode. A hysteresis band is used in the control algorithm to reduce the number of switching.

4.3.1 Implementation of the Grid Connected Controller

The proposed control algorithm for grid connected operation is implemented in the laboratory using a self excited induction generator driven by a wind turbine simulator. A separately excited DC motor which is coupled to the induction generator is simulated to follow the torque developed by the wind turbine. The wind speed profile is fed to the PC based wind turbine model from a file. The flow chart of the implemented grid connected control algorithm is shown in Figures 4.3. Figure 4.3 shows the control algorithm in which grid connection decision is taken based on voltages and frequencies at the generator and grid sides; and disconnection decision is taken based on the current flow between the generator and the grid, as well as the generator speed. The implemented control sequences in Figure 4.3 are as follows. Assume low wind speed (say at 6 m/sec) and the generator is running at low speed. As the excitation capacitors are connected at the generator terminal, due to the increase in wind speed (let say at 7.3 m/sec), the generator reaches the self excitation and the voltage is induced at its terminal. A delay is introduced in the controller to allow transients to diminish, so that the controller decision is based on steady state values. The controller then measures the generator and grid voltages and frequencies via instrumentation shown in Figure 4.2, in order to check the grid connection conditions. Generator terminal voltage and frequency should be more or less equal to the grid voltage and frequency which are set in the program as the grid connection conditions. As this condition is true at the given wind speed, the controller connects the system to the grid via soft-starter and wait such that transients die out after the connection. When connection is set up, the controller monitors the generator speed and the current flow between the generator and the grid by receiving the information about current and generator speed using measuring instrumentation. Upon this measurement, if the controller detects

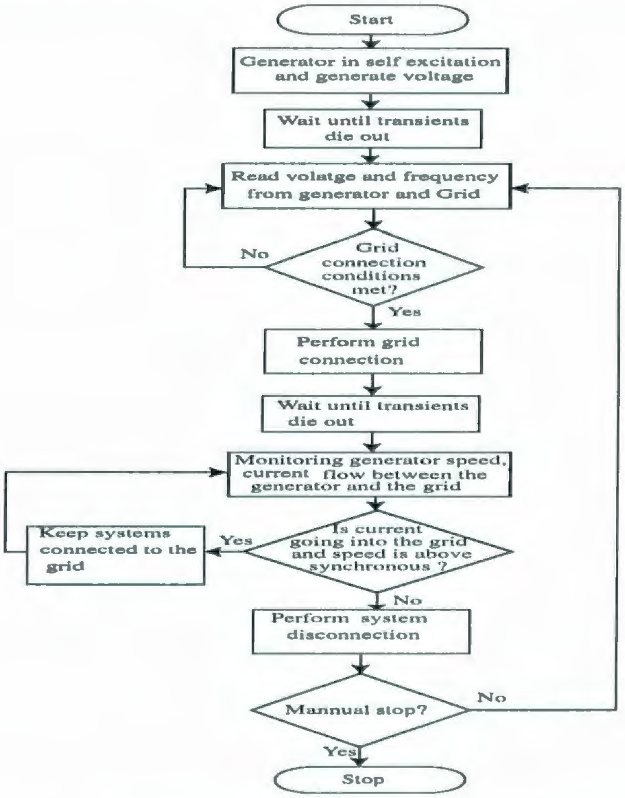


Figure 4.3: Flow chart of the control algorithm while disconnection is based on current and speed

that the generator is delivering current to the power grid and the generator speed is above or around the synchronous speed, then the controller keeps the system connected to the grid and again keeps checking the current delivered by the generator and the speed of the generator. Now assume the wind speed is reduced to 5 m/sec, so the voltage generated at the generator terminal is reduced and hence the generator speed is also reduced. As a result the turbine and generator will act as the load which draws current from the grid. As the controller is programmed to perform disconnection as soon as it detects the current is coming back to the system from the grid, if that happens the system controller disconnects the system from the grid using *relay_2*. Subsequent to the disconnection, the system can either be stopped manually or can allow to operate at off-grid mode. The control code in Mikrobasic is given in appendix B. Figure 4.4 shows the flow chart of the proposed algorithm, which has been implemented in PIC micro-controller, while the connection decision is taken using voltage and frequency measurement, and the disconnection is performed using power measurement.

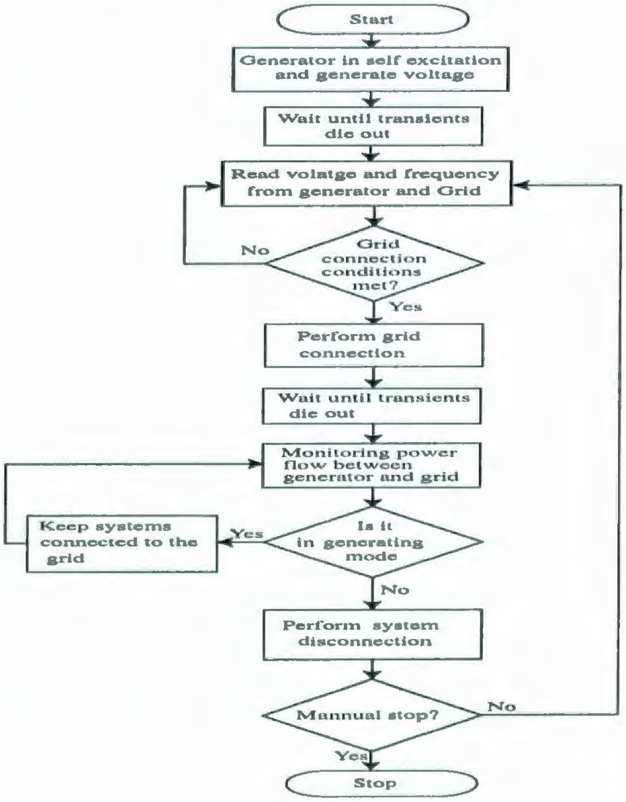


Figure 4.4: Control sequences while disconnection is based on power measurement

The disconnection strategy based on power measurement is more accurate and less complex as this method requires only to acquire and monitor a single parameter. The operation of the algorithm can be expressed as follows. Assume wind speed is low; as a result the generator is running at lower speed. After few seconds, the wind speed increases (let say 7.3 m/sec) and the generator speed also increases. Voltage is induced at the generator terminal while its speed goes above certain rpm because self-excitation capacitors are already connected at the generator terminal. The system controller reads the voltages and frequencies at the generator terminal and grid side. The parameters measurement instrumentation is shown in Figure 4.5. After performing the grid connection, a delay is used to avoid the transients and let system reach a stable operation. The system controller monitors the power flow between the generator and the grid once the system is connected to the grid. The power measurement is accomplished using instrumentation circuitry shown in Figure 4.5. If the power is positive, the controller maintains the grid connection, otherwise if the generator switches to motoring

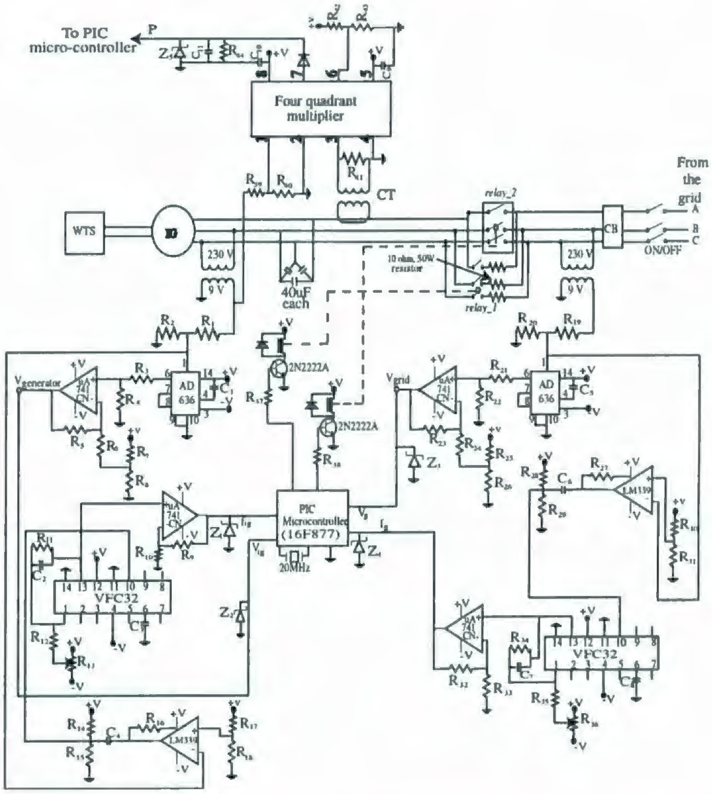


Figure 4.5: Schematic of the instrumentations for voltage, frequency and power measurements

mode (say wind speed is low), then controller disconnects the generator from the grid. To detect the power whether it is positive or negative, a logic explained in controller design section is programmed in the system controller. After the disconnection, the controller again monitors the voltage and frequency at the generator and grid side. Within few seconds, the wind speed increases but may not enough to meet the grid connection conditions. In such case, the controller still keeps checking the conditions. If the situation is such that the wind speed further increases (say at 8 m/sec) and the system controller detects that the grid connection conditions are met, the controller will connect the system to the grid otherwise not. Once it is connected, the controller again checks the power status. The operation will be repeated as long as the wind turbine is in operation. The detail control code for this controller is given in appendix C. Figure 4.6 shows the photograph of the grid mode instrumentation in laboratory environment.

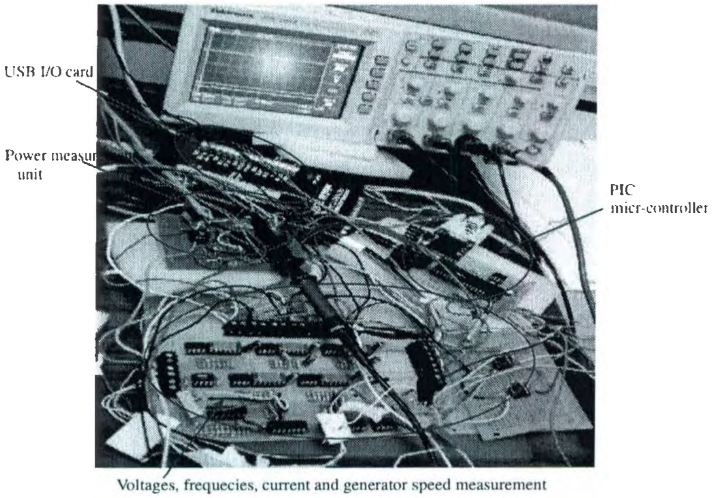


Figure 4.6: Photograph of the grid mode instrumentation at the laboratory

4.4 Off-Grid Mode Controller Design

Suppose the wind power generation system is running in grid connected mode. During operation in this mode, the system controller monitors the current or power flow between the generator and the grid, generator speed and the grid status. The main purpose to design this control mode (shown in Figure 4.7) is to take care of the wind turbine system during the grid absence. Grid unavailability may occur due to the grid failure and maintenance or repair. The grid unavailability is detected by the controller using grid voltage sensing. If the voltage sensed by the controller is near or equal to zero, the controller ceases the system connection from the grid. After disconnection from the grid, the controller sends a signal D_2 to the *relay_3* to initiate the connection between the generator and the dump load. As soon as *relay_3* turns on, the electronic PI controller triggers the phase control relay to connect the system to the dump load. The PI controller is designed in such a way that it works as follows. The object of the controller is to maintain rated line-to-line/phase voltage at the load terminal. The voltage at the output of the voltage sensor due to the rated line-to-line voltage at the load terminal is determined as the reference voltage. If the feedback voltage is less than or equal to the reference voltage then no control action is needed to chop the voltage at the load terminal. The load terminal voltage at which the feedback voltage is less or equal to the reference voltage is basically less or equal to the rated line-to-line/phase voltage. If the feedback voltage is greater than the reference voltage, the load terminal voltage will be higher than the rated value which needs to be chopped to keep the rated voltage at the load terminal. In this case the PI controller sends a control value to trigger the phase control

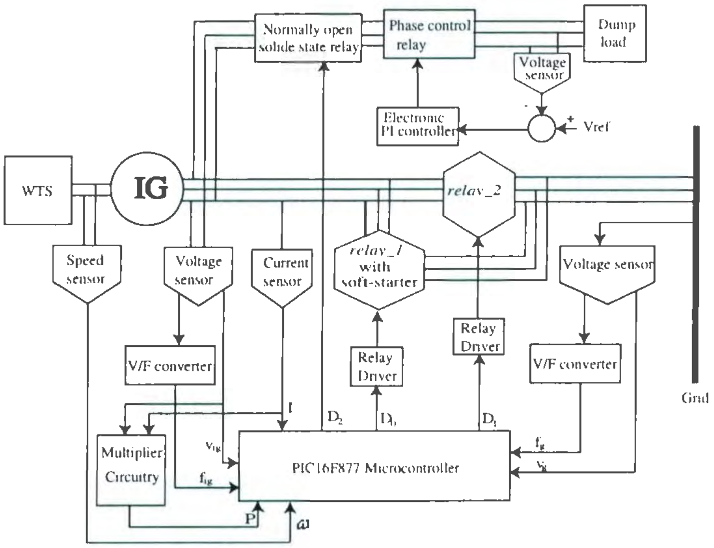


Figure 4.7: Block diagram representation of the system controller during off-grid control mode

relay and regulates the voltage at the load terminal. The input of the phase control relay varies from 0-10V upon which the output voltage is regulated. At the same time, the system controller checks the grid status. Once the grid is recovered, the system controller checks the grid connection conditions. If the conditions are met, the system controller sends a signal (D_2 = low) to the solid state relay to disconnect the system from the dump load and connects the wind turbine system back to the grid, otherwise the system controller keeps checking the conditions.

4.4.1 Implementation of the Off-Grid Mode Controller

Figure 4.8 shows the control flow chart during off-grid connection when the disconnection from the grid is on the basis of power measurement. In this control algorithm (given in appendix D), power flow between the generator and the grid is considered as the disconnection parameter rather than current. The measurement of power along with other system parameters is shown in the instrumentation circuitry in Figure 4.9. Suppose system is running in grid connected mode. During the grid connected operation, the system controller monitors the power flow between the generator and the grid, and also voltage from the grid side. The rated voltage present at the grid terminal indicates that the grid is available. While the grid is present and the power is going into the grid, the system controller keeps the wind turbine system connected to the grid. On the other hand, if grid is available however the power is drawn by the generator rather sending to the grid, the controller will disconnect the system from the grid. If not, such as grid is not available and generator has lost its self excitation due to an effective short circuit placed across it or power is going back to grid, the system controller performs the disconnection of the wind turbine system from the grid and connects it to the dump load using solid state relay. Generator will self excite again as soon as it is disconnected from the grid. Normally open solid state relay is used to keep the wind power generation system isolated from the load during grid connected mode. Once it is connected to the dump load, the electronic PI controller comes in operation and regulates the load terminal voltage using phase control relay. The electronic controller sends control signal to phase control relay

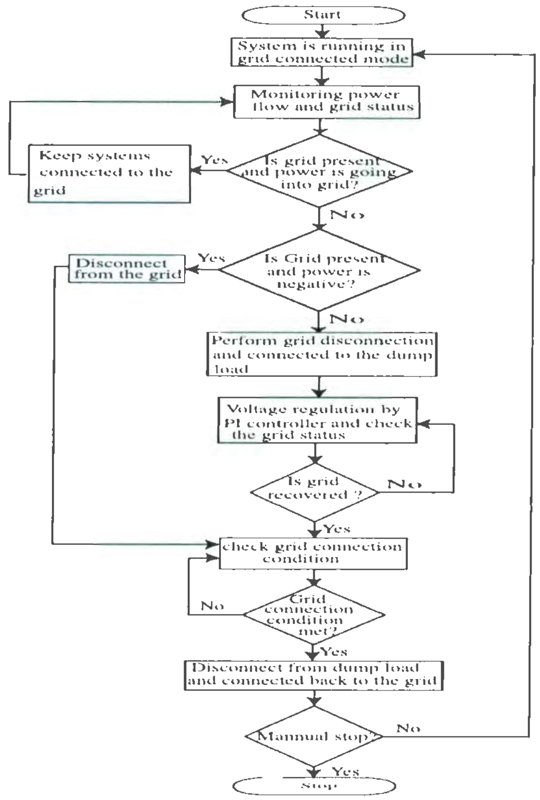


Figure 4.8: Flow chart of the off-grid control sequences while disconnection is based on power measurement

to chop the excess voltage at the load terminal generated by the wind turbine system. The frequency of the generated voltage in isolated mode was not a concern in this research. The implementation of the PI regulator using operational amplifier is shown in Figure 4.10. During this off-grid operation, the controller keeps checking the grid status by measuring the voltage at the grid terminal. As soon as the grid is recovered, the system controller monitors the grid connection conditions. While the grid connection conditions are met, the system controller disconnects the wind turbine system from dump load and connects the system back to the grid. The process will be repeated until the wind turbine is in operation. Figure 4.11 shows the photograph of the instrumentation for off-grid control mode in laboratory.

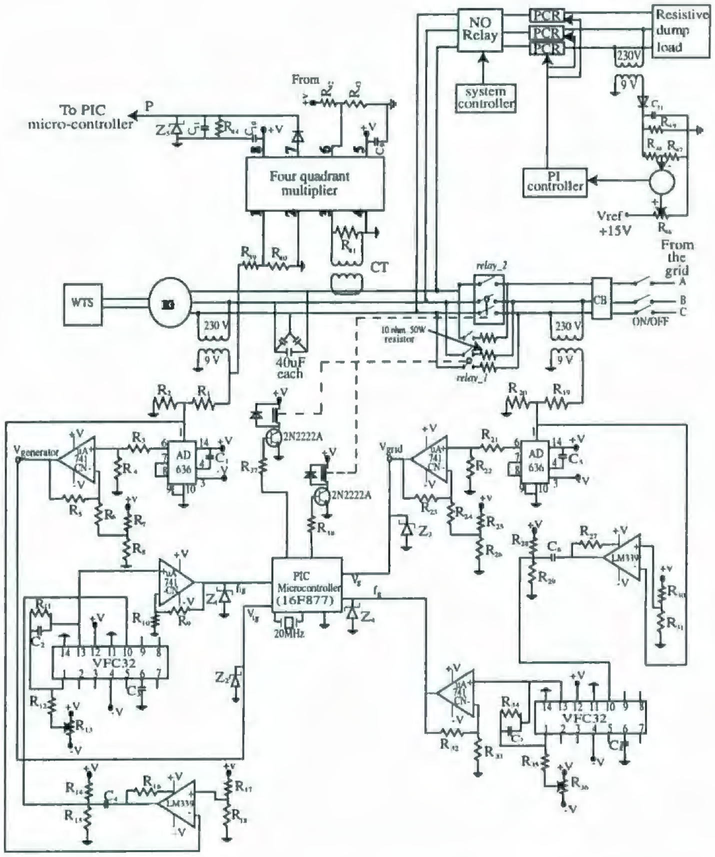


Figure 4.9: Instrumentations for voltage, frequency, power measurements, and voltage regulation during off-grid control mode

Implementation using current measurement

Flow chart of the off-grid control sequences while disconnection is taken on current measurement is shown in Figure 4.12. During the grid connected operation, the system controller will monitor the current flow between the generator and the grid, generator speed, and also voltage from the grid side. The rated voltage present at the grid terminal will indicate that the grid is available. While the grid is present and the current is positive, the system controller will keep the wind turbine system connected to the grid. On the other hand, if grid is available and the current is negative, the controller will disconnect the system from the grid. If not, such as grid is not available but the voltage at the generator terminal is decaying due to the current drawn by the load connected to the grid, the system controller will perform the disconnection of the wind turbine system from the grid and connects it to the dump load.

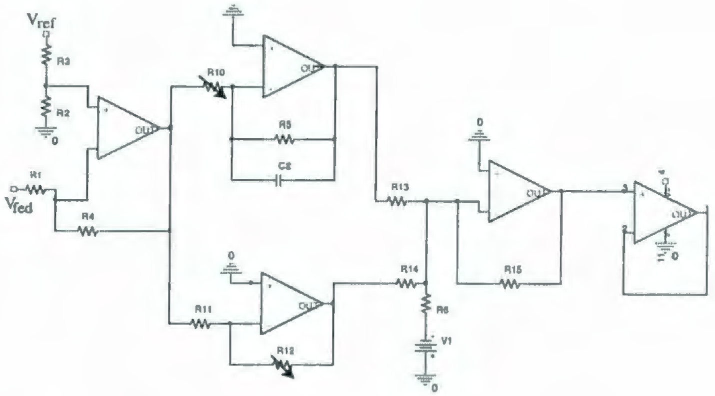


Figure 4.10: Implementation of an electronic PI controller

While it is connected to the dump load, the electronic PI controller will come in operation and regulate the load terminal voltage using phase control relay. The electronic controller sends control signal to phase control relay to chop the excess voltage at the load terminal supplied by the wind turbine system. The implementation of the PI regulator could be accomplished using operational amplifier shown in Figure 4.10. During this off-grid operation, the controller keeps checking the grid status by measuring the voltage at the grid terminal. As soon as the grid will recover, the system controller will monitor the grid connection conditions. While the grid connection conditions are met, the system controller will disconnect the wind turbine system from dump load and connect the system back to the grid. The process will be repeated until the wind turbine is in operation. The measurement of all parameters during the entire operation could be implemented by the instrumentation circuitry shown in Figure 4.13.

4.5 Soft-starter Design and Implementation

The intensity of small wind power system expansion depends on various factors related to technical, economical, environmental, governmental, and regulatory issues. One of the important technical and economical issues such as soft-connection between the wind power generator and the grid. Soft-starter basically provides soft-connection between the wind power generator and the grid through an electrical device for a very short time to limit the initial current,

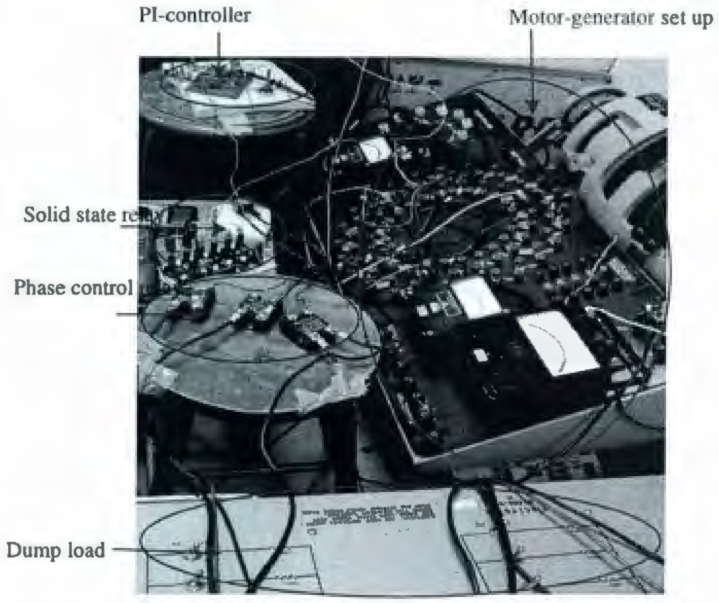


Figure 4.11: Photograph of the instrumentation for off-grid operation

and after that time elapsed it performs the connection directly to the grid and bypasses the device. Power resistors based soft-connection technique is shown in Figure 4.14 which consists of power resistors through which the system is first connected to the grid for a few milliseconds and then it bypasses to set up the connection via main contactor. To limit the current during the grid connection using power resistors based soft-starter does not require any control logic unlike in other kinds of soft-starter(such as SCR/TRIAC), which makes its more simplified and meaningful for small wind energy conversion system. The design and implementation of a power resistors based soft-starter strategy for small grid connected wind turbine is shown in Figure 4.15. The soft-starter consists of three power resistors each of 6 ohm and 100W, two relays and relay driver circuits. Three power resistors are connected in series with each line via the *relay_1* and the *relay_2* is connected in between the induction generator and the grid as the main contactor. This type of soft-starter works first by connecting the system to the grid through power resistor using *relay_1* and after a suitable time the connection is set up via main contactor by switching *relay_2*. Time difference between switching *relay_1* and *relay_2*, and the suitable values of the power resistors are determined through experimental investigations. Investigations are carried out on a micro-controller controlled small grid con-

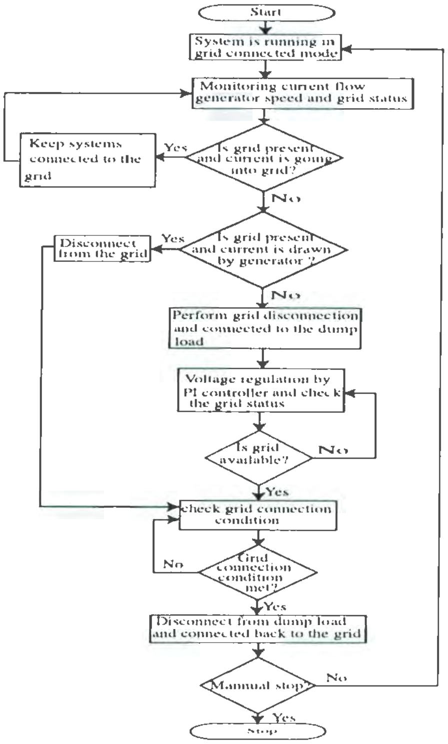


Figure 4.12: Flow chart of the off-grid control sequences while disconnection is based on current measurement

nected wind energy conversion system. Relays are operating on 12V DC coil which is driven by driver circuits. The driver circuits are simply based on PNP transistor where those are working as a switch. The transistors are activated/deactivated by the control signal (logic 0-5V) coming from the system controller. The voltage applied across the relay coil is limited using resistors R_4 and R_6. The major implementation issues were to determine the proper values of the power resistors and also to identify the switching time difference between two relays. Because more or less value of the resistors causes more power loss or less effective in reducing the inrush current. Again, more time difference takes longer time to a stable current which results more stresses on the soft-starter elements and less time difference between the relays also results unexpected trips of the protection circuit breaker. Those issues are resolved through several experimental tests on a controlled small wind turbine system. During disconnection, the system controller only needs to send a low signal to turn off *relay_2*.

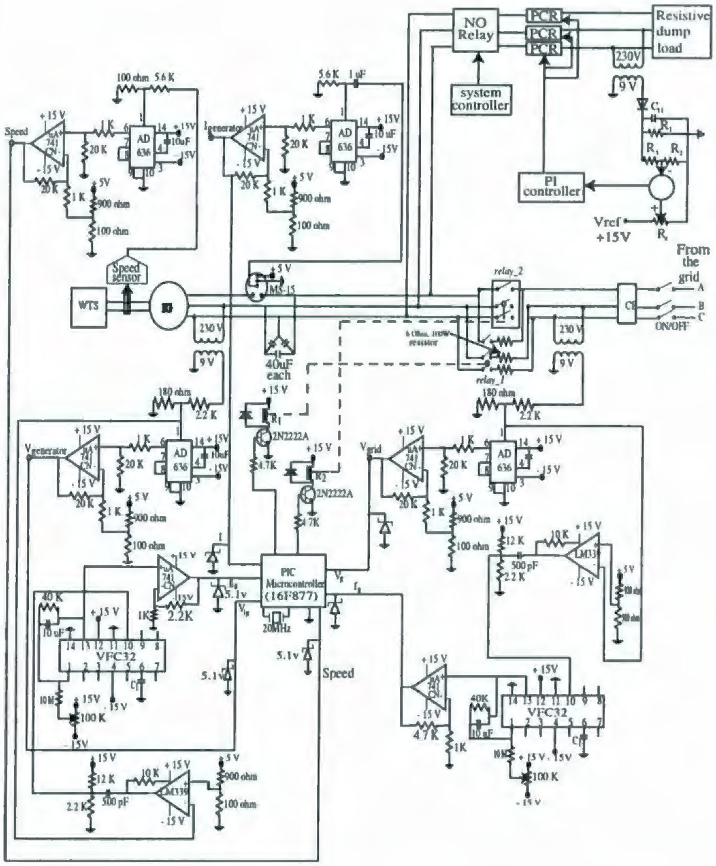


Figure 4.13: Schematic of the instrumentations for system parameters measurements during off-grid control mode

4.6 Anti-Islanding Implementation

Islanding, as mentioned earlier, occurs when a portion of the distribution system becomes electrically isolated from the remainder of the power system, yet continues to be energized by the generation system connected to the isolated subsystem. Basically, detect the loss of grid power and keep the subsystem disconnected from the grid until it is recovered are the main aspect of anti-islanding implementation. Otherwise, islanding causes a hazard to utility and customer equipment, maintenance personnel and the general public. This research also addresses this issue while the system controller operates. The system controller design and implementation shows that it can easily identify the grid unavailability by receiving the grid information. While the system controller could detect the grid is absent, it simply disconnects the system from the grid and maintains the operation of the system in off-grid mode. The

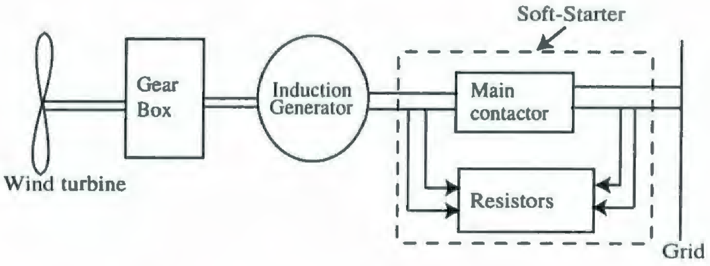


Figure 4.14: Power resistors based soft-connection strategy

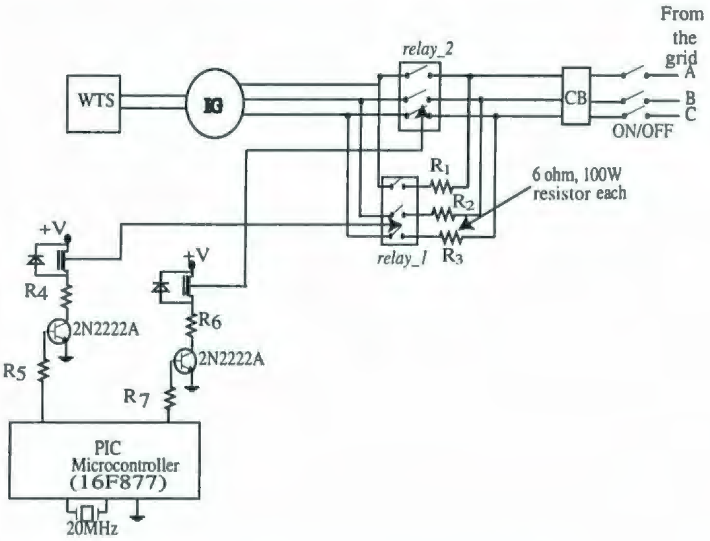


Figure 4.15: Implementation of Soft-starter

designed controller will never connect the wind turbine to the grid when grid is absent hence islanding situation will never occur.

4.7 Summary

Design and implementation issues of a low cost system controller for a small induction generator based wind turbine system are presented in this chapter. The operation of the system controller is considered in two different modes under real time conditions such as lack of wind, low wind, wind is enough to produce power at the grid frequency. Although the controller decision to connect the system to the grid is based on voltages and frequencies at the generator and grid terminal, the disconnection decision is taken based on two parameters such as power or current flow between the generator and the grid. The complete instrumentations to operate two modes separately and flow chart of the control algorithm is also explained. Soft-connection between the system and the grid is performed by a power resistors based soft-starter which is also presented here. Finally, the islanding situation and the controller operation during islanding is described in this chapter.

Chapter 5

Experimental Test Results

This chapter describes several test results and detailed discussions of a micro-controller based system controller for a small induction generator based grid connected wind turbine. The system controller is tested to perform the connection/disconnection of the wind turbine system from the grid in two real time situations such as lack of wind and enough wind to produce power. Another investigation and test results on a power resistors based soft-starter are also presented in this chapter. Finally, the voltage regulation by a phase control relay based electronic PI controller test results during off-grid mode are also presented.

5.1 Introduction

The operation of the system controller during grid connected mode and off-grid mode described in chapter 4 was implemented and tested in laboratory environment using a PIC micro-controller. The grid connected control mode was implemented using micro-controller and the off-grid control mode was implemented using micro-controller, electronic PI controller and dump load. It was desired that the system controller would connect/disconnect the wind turbine generation system from the grid based on system parameters measurements. The proposed controller is working as expected which also indicates the performance of the developed low cost instrumentation. Moreover, an investigation was also necessary to ensure the soft-connection between the wind power generator and the grid. The investigated result shows the performance of the proposed soft-connection strategy and proves the effectiveness in small grid connected wind energy conversion system. The entire experimentation was done on a small wind energy conversion system which consists of WTS coupled with a self excited induction generator. The discussion of the test results achieved from the system controller and soft-connection technique is presented in the following sections.

5.2 System Controller Test Results for Grid Connection

The system controller is tested while the connection decision is taken based on the measurement of the voltages and frequencies from both the generator and grid terminal; and the disconnection decision is taken based on either current, generator speed or power feedback.

5.2.1 Current and Speed Feedback Controller

The experimental test results of the system controller based on current and speed feedback are shown in the Figures 5.1 and 5.2. During the period before 3 seconds, the generator was running at the low wind speed (less than 6 m/sec). As the wind speed (7.3 m/sec) increases cause the generator terminal voltage and frequency increase. Due to the grid connection condition met at t=3 seconds, the controller connects the system with the grid. Figure 5.1 shows the generator current when the induction generator is connected to the grid through the soft-starter. As soon as (at t=3 seconds) the controller initiate to connect the system to the grid through soft-starter, there is a surge in the current. The series power resistors in soft-starter limit the surge in current. After a delay of 2 seconds, the controller directly connects the system to the grid and the generator current decays smoothly to a steady state value. After sometimes the wind speed again goes to lower value i.e. 5.5 m/sec. Due to the lack of sufficient wind, the generator terminal voltage is reduced and the generator acts as a motor which will start to draw current from the grid. The magnitude of the current drawn at the motoring mode (below synchronous speed) is higher than deliver as a generator (above

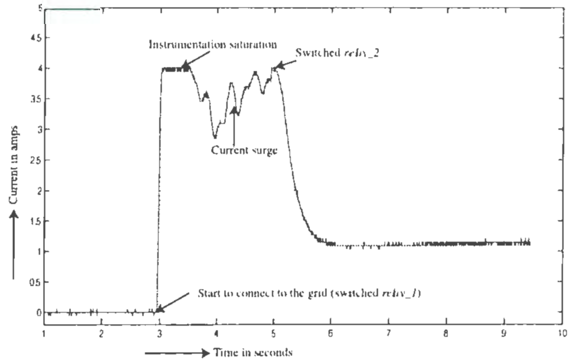


Figure 5.1: Current flow between the generator and the grid during grid connection

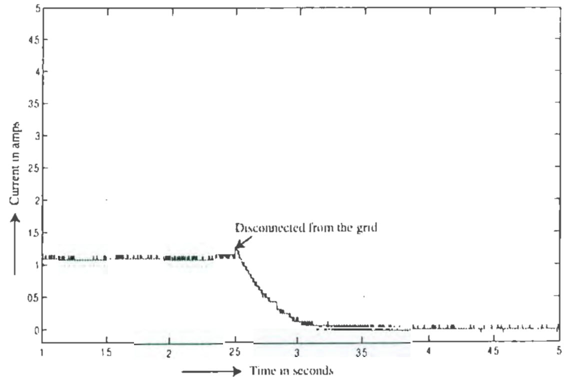


Figure 5.2: Current flow between the generator and the grid during grid disconnection

synchronous speed). Figure 5.2 shows the generator current when the controller disconnects the system from the grid. During t=1 to 2.4 seconds the current is same as the value of the grid connected operation. As the wind speed drops the current magnitude goes higher and based on it, the controller disconnects the system from the grid and the generator current decays to zero. Although the system is disconnected at t = 2.5 seconds, the current should go to zero at that time, however, the current completely goes to zero at t = 3.2 seconds which happens due to the instrumentation ($\tau = RC$) time constant. Figure 5.3 and 5.4 shows what happens to the generator speed after connection and disconnection from the grid respectively.

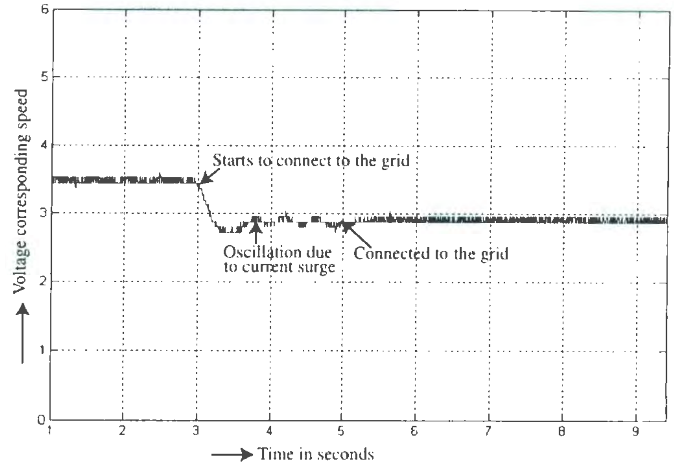


Figure 5.3: Generator speed during grid connection

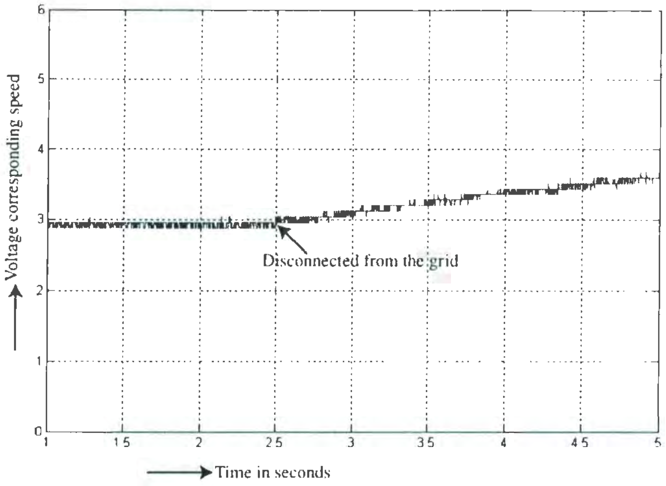


Figure 5.4: Generator speed during grid disconnection

5.2.2 Controller Based on Power Measurement

This control technique evolves on the measurement of voltages and frequencies for grid connection and power for grid disconnection. The experimental test results are shown in Figures 5.5, 5.6 and 5.7. Figure 5.5 shows the power flow status between the generator and the grid during wind variation. At the very beginning the generator is running at low wind speed. As wind speed increases to 7.3 m/s (see figure 5.6), voltage and frequency at the generator terminal increase. The controller is checking the voltages and frequencies from the generator and grid sides. At $t = 73.5$ seconds, the system is connected to the grid as the system connection

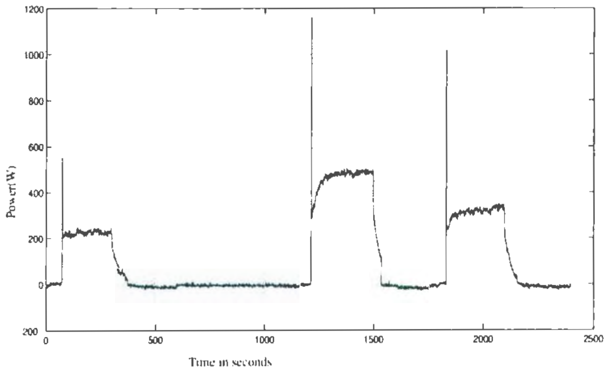


Figure 5.5: Power output during grid connection and disconnection

conditions are met. After connection, power is positive which indicates the generator is in generating mode. At $t = 300$ seconds the wind speed drops from 7.3 m/s to 5.5 m/s. In such case the power decays. As soon as the power goes negative (at about $t = 400$ seconds) i.e. generator is going to the motoring mode, the controller disconnects the system from the grid.

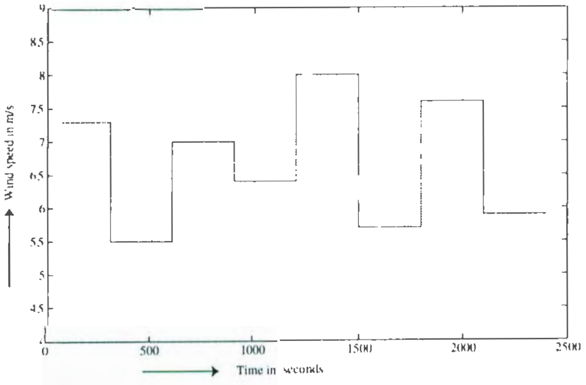


Figure 5.6: Variation in the wind speed used during system controller testing

During the period t=600 to 900 seconds, the wind speed is about 7 m/s, however the voltage and frequency from the generator and grid has not matched. The same situation happens when wind speed is about 6.4 m/s. At t=1200 seconds, wind speed is again increases to 8 m/s and when the system parameters reach the system connection condition, the controller connects the system to the grid. The same sequence was repeated until t=2400 seconds. During grid connection at each time, there is a transient for a very short duration due to the current surge. The transient response during the system connection to the grid is shown in figure 5.7. The initial surge in power is about 2.75 times of the stable power due to the connection through the soft-starter which is significantly reduces than the situation when the system is directly connected without any soft-starter.

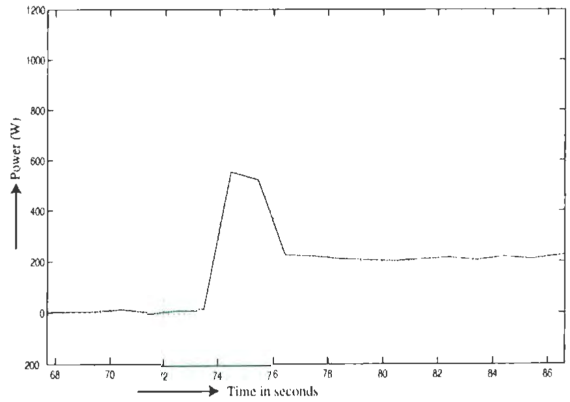


Figure 5.7: Transient in power during the system connection to the grid

5.3 Test Results for Off-Grid Mode

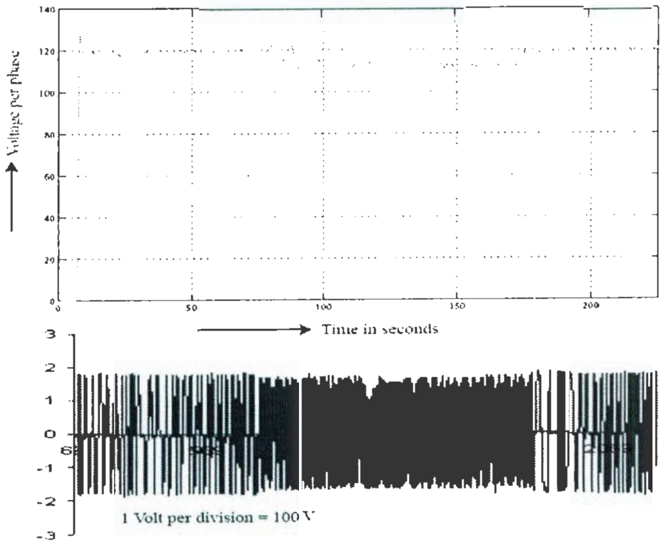


Figure 5.8: Load terminal voltage during off-grid mode

Both the system controller and PI regulator tests were performed together during the off-grid operation. The system controller was assisted to connect/disconnect the system with

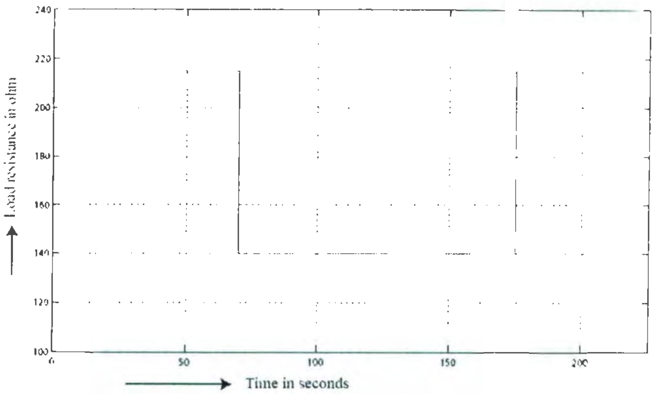


Figure 5.9: Change in load during off-grid operation

the grid, grid status checking and connect the system with the dump load. The PI regulator was able to maintain more or less rated load terminal voltage due to the variation in load or wind speed. Variation in the load terminal voltage with the change in load are shown in Figures 5.8 and 5.9. While the grid was absent, the system controller disconnected the system from the grid and connected to the dump load. In Figure 5.8, at $t = 5$ seconds, the system is connected to the dump load while the load was 215 ohm per phase. At $t = 70$ seconds, the load was changed to 140 ohm per phase i.e. load was increased. As a result the terminal voltage is changed in a small amount and remains constant until the next load change. Again load was reduced to 215 ohm which causes the terminal voltage change by a small amount and later kept more or less constant until the next change in load. The lower plot of Figure 5.8 shows the alternating voltage at the load terminal which is acquired by 100X probe and oscilloscope. The voltage during $t = 5$ to 70 seconds is about 1.69V peak which is equivalent to (1.69/1.414 =1.195x100=119.5) 119.5V in each phase. Again due to the change in load, although the terminal voltage is dropped by a small amount, it always remain more or less constant. Figure 5.10 shows the PI regulator performance while there is a step change in wind speed. The load terminal voltage is constant from $t = 0$ to 65 seconds while the wind speed is 7.8 m/sec. The wind speed step change is shown in figure 5.11. At $t = 65$ seconds, the wind speed is changed to 8.15 m/sec. Due to change in the wind speed, the load terminal voltage also increases however the PI regulator tries to keep the load terminal voltage more or less constant at about 120V.

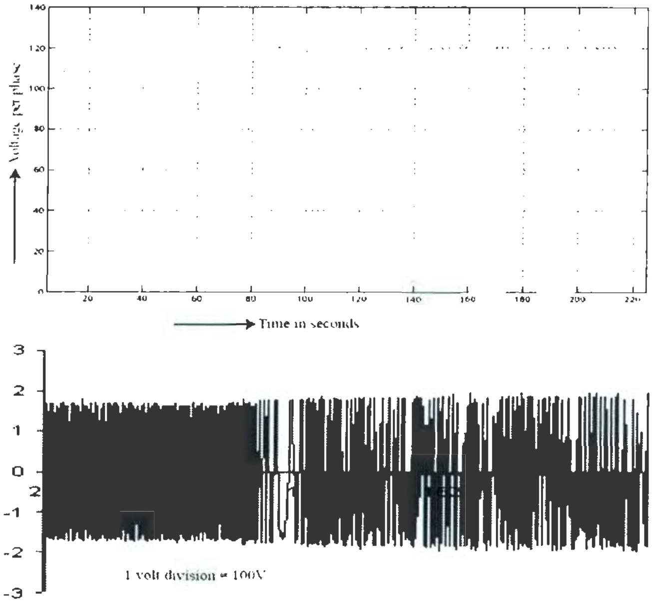


Figure 5.10: Load terminal voltage due to wind speed change during off-grid mode

5.4 Soft-starter Test Results

Investigation for determining the suitable time difference between switching of soft-starter relays and also to find out the suitable value of the power resistors is carried out on a micro-controller controlled small grid connected wind turbine system in laboratory environment. The experimental test results are shown in the Figures 5.12, 5.13 and in Figure 5.14. After a number of tests, suitable switching time delays between soft-starter relays is determined. Figure 5.12 shows the generator current when the induction generator is connected to the grid through the soft-starter. The controller connects the system to the grid through a soft-starter using *relay_1*. After $t = 450$ milliseconds, soft-starter is bypassed by switching *relay_2* and the system is directly connected to the grid. In this test results, current is surging to 19.8A (RMS) (4x7/1.414 = 19.8A) that is 3.2 times the rated current of the generator. The rated values of the generator are given in [70]. Figure 5.13 shows the similar test results, however, the switching time difference between the relays is 350 milliseconds. This result shows the initial surge in current is about 1.62 times the rated current of the induction generator. Therefore, reduction in the switching time difference between two relays provides better result. Proper selection of this time delay is very critical. This time delay and resistor values were achieved

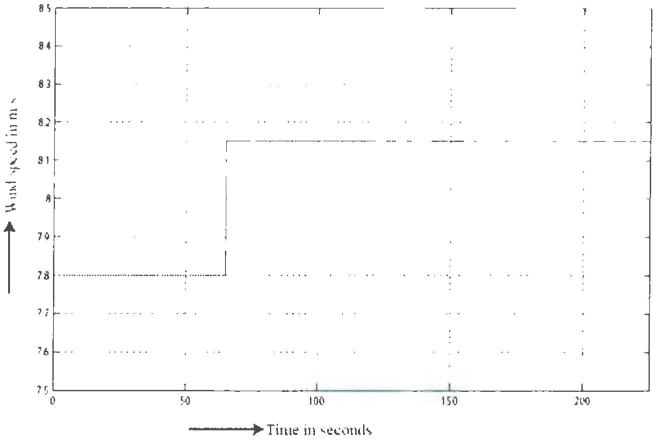


Figure 5.11: Step change in wind speed during off-grid mode

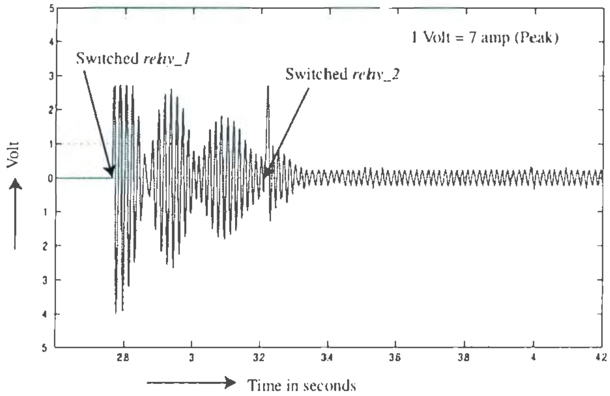


Figure 5.12: Current flow between the generator and the grid during the grid connection. (Switching time difference between the relays is 450 milliseconds)

after analyzing a number of test results on the basis of trial and error. In a SCRs based soft-starter, initial surge in current can be about 3 times of the rated current of the generator [39]. So the proposed soft-starter able to limit the initial surge in a significant amount. Further reduction in the time delay always led to tripping of series three-phase 10A protection circuit breaker. The circuit breaker always trips during the connection of the system without any soft-starter. Based on the above discussed test results, the most suitable switching time difference (i.e. 350 milliseconds) which is the best suited for the system was found. Figure 5.14 shows the generator current when the controller disconnects the system from the grid. In this case grid disconnection occurs at t=1.35s. It happens due to a drop in wind speed.

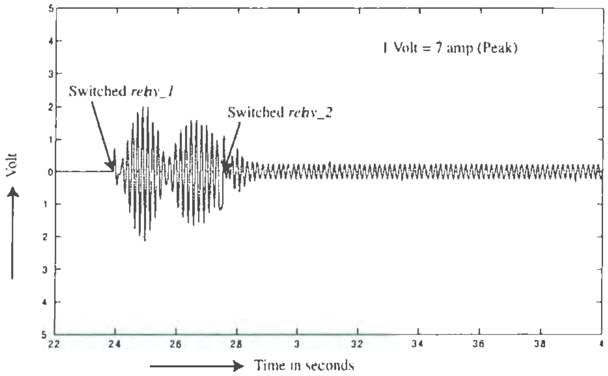


Figure 5.13: Current flow between the generator and the grid during the grid connection (Switching time difference between the relays is 350 milliseconds)

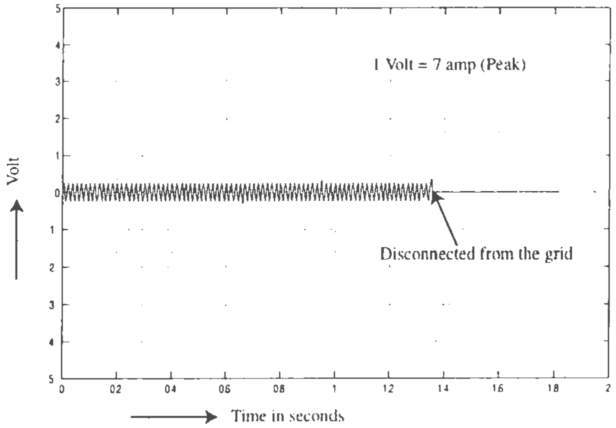


Figure 5.14: Current flow between the generator and the grid during the grid disconnection

Generator current drops to zero as soon as it is disconnected from the grid. An AC/DC current probe (A622, Tektronix) and a four channel digital storage oscilloscope (TDS 2014, Tektronix) were used to measure the alternating current flowing between the generator and the grid. However, the controller connection/disconnection decision is taken based on the measurement of the RMS value of the current. The RMS value of the current is measured using an AD636 RMS to DC converter which is described in chapter 3.

5.5 Summary

The test results of the system controller during grid connected mode and off-grid mode are described in this chapter. The system controller performs as expected to maintain the grid interconnection. The test results for soft-connection between the generator and the grid also prove the soft-starter effectiveness during the grid connection process.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The main focus of the thesis is the development of a low cost control system for small induction generator based grid connected wind turbines. A PIC micro-controller is preferred as the controller which is programmed to make the wind turbine system operational and supply power to the grid. The controller operation is based on the measurements of system parameters which are achieved by the designed instrumentation. A wind turbine simulator is also developed to provide the test platform of the proposed control systems and associated instrumentation in laboratory environment.

Wind turbine simulator

In the first place, a separately excited DC motor simulation as wind turbine rotor is implemented. The steady state characteristics of the wind turbine are incorporated to the developed wind turbine simulator. To reflect the inertia of such wind turbine, the inertia of DC motor and induction generator is considered. A recursive type PI control algorithm is implemented to simulate the DC motor which ensures that the DC motor follows the wind turbine torque. Due to the simulation of the steady state model of the wind turbine, the response of the wind turbine simulator is slow hence it cannot simulate the fast changing wind turbulence. However, tests results on the simulator are performed at constant wind speed.

step change and a narrow range variation in wind speed which show acceptable performance. Such a simulator is very effective to develop and test the control system for small wind power generation system.

Current feedback control system

In the second phase, a micro-controller based system controller is developed and tested to connect/disconnect the generation system and also to maintain the connection between the wind power generator and the grid. The controller is developed for both grid connected and stand-alone mode. In current feedback control system, the controller receives voltages and frequencies from the generator terminal and grid side, and based on these measurements, the controller connects the generator with the grid. To make a decision for the generator disconnection from the grid, the controller always monitors the current flow between the generator and the grid, and also generator speed. The controller response during the connection/disconnection of the system is studied by observing the current and generator speed. Test results are performed on current feedback controller based on real time conditions such as lack of wind, low wind and wind is sufficient to produced power.

Power feedback control system

Furthermore, an alternative method called power feedback control system is implemented to connect/disconnect the wind turbine system with the grid. In this control method, although the controller connects the system with the grid based on voltage and frequency measurements, the disconnection decision and to maintain the connection is accomplished on power measurement. The power flow which is either positive or negative, that depends on the wind speed. The controller keeps system connected to the grid while the power is positive; otherwise it disconnects the system from the grid. This control system provides quick response for grid disconnection as the decision is based on only one parameter. Investigations are carried out on this controller at different wind conditions which shows the results as expected.

System Instrumentation

At this stage, low cost system instrumentation is developed and tested for the system controller. The purpose of the instrumentation is to measure the system parameters such as voltages, frequencies from generator and grid sides, current and power flow between the generator and the grid, generator speed, and torque of the DC motor. Such instrumentation is very useful for reliable operation of the system controller. Otherwise the improper design of the instrumentation may read incorrect parameter value which affect smooth operation of the controller.

Soft-connection Strategy

Thereafter, an investigation is carried out on soft-connection strategy between the generator and the grid. For this purpose a power resistors based soft-starter is designed and tested. The values of the power resistors are determined on experimental investigations. The suitable time difference between the switching of the two relays is also found by experimentation. The effect of the more or less time difference between the switching of the two relays is discussed. The soft-starter has been tested by considering two different real time conditions using MUN WTS. Such soft-starter is much cheaper and operated without any control which is a good technical benefit for small induction generator based wind turbines.

Voltage Regulation During Off-grid Mode

Finally, an investigation is carried out on off-grid control mode. Such control mode is considered while grid is absent but the wind is available to produce power. The time, at which the system controller detects that the grid is absent, it disconnects the wind turbine system from the grid and connects to the dump load. During off-grid operation, it is necessary to modulate the voltage at the load terminal due to the variation of the wind speed or load. For this reason, an electronic PI controller is designed to chop the excess voltage and to maintain the rated voltage at the dump load terminal. The PI controller is implemented using operational amplifier which sends control signal to a phase control relay.

The summary of outcomes of this research is followings.

1. Development of a wind turbine simulator to provide a test bed for the system controller. A discrete PI controller is designed to simulate a separately excited DC motor as wind turbine rotor.
2. Design and development of a novel micro-controller based system controller for small induction generator based grid connected wind turbines. Two different control methodologies (current and power feedback) were developed and tested.
3. Development of instrumentation to measure the system parameters and test the performance with the system controller.
4. Design and development of a novel control system during off-grid operation of the grid connected wind turbine. The off-grid situation may occur due to failure of the grid or unavailability of the grid.
5. Design and test of a power resistors based soft-starter for a small induction generator based grid connected wind turbine.

6.2 Recommendations

In the developed wind turbine simulator, steady-state characteristics of the wind turbine model are incorporated. However to reflect the real time behavior of the wind turbine, it is very significant to add the dynamics of the wind turbine. In addition, to operate the wind turbine beyond the rated wind speed, pitching mechanism can be considered. These requirements in a WTS could make it more realistic which would be another good option for designing WTS to test the proposed system controller for grid connected wind turbines.

The WTS should also be able to extract the maximum power from the load. In order to achieve maximum power, the maximum power point tracker could also be investigated for the developed WTS.

The developed system controller has been studied for two real time situation such as lack of wind and enough wind to produce power. Furthermore, the controller is needed to be investigated for over and under voltage conditions. In addition, the controller is also needed to be further studied during abnormal frequency situation. The system controller was expected to implement according to the installation standard described in chapter 3 which needs further improvement.

During off-grid control mode, power feedback control system was engaged while the voltage at the load terminal was regulated by the phase control relay based electronic PI controller. Voltage regulation using electronic PI controller with current feedback control system is left for further investigation. Voltage regulation is only considered for resistive load however for inductive and capacitive load are also needed to be considered for further work.

Publications List

Test results have been published in the following publications during the course of the Master of Engineering program.

Conference Papers

1. **R. Ahshan**, M. T. Iqbal, George K. I. Mann, "Power resistors based soft-starter for a small grid connected induction generator based wind turbine," *Proceedings, The 17th Annual IEEE Newfoundland Electrical and Computer Engineering Conference*, November 8, 2007 St. John's, NL.
2. **R. Ahshan**, M. T. Iqbal, George K. I. Mann, "Performance of a controller for small grid connected wind turbine," *Proceedings, 7th IEEE Electrical Power Conference*, EPC07, October 25-26, 2007, Montreal, Canada.
3. **R. Ahshan**, M. T. Iqbal, George K. I. Mann, "Small induction generator based wind turbine simulator," *Proceedings,The 16th Annual IEEE Newfoundland Electrical and Computer Engineering Conference*, November 9, 2006 St. John's, NL.

Journal Papers

1. **R. Ahshan**, M. T. Iqbal, George K. I. Mann, "A new control approach for small grid connected wind turbine," *Wind Engineering Journal*, Vol. 31, No. 5, 2007.
2. **R. Ahshan**, M. T. Iqbal, George K. I. Mann, "Controller for small induction generator based wind turbine," *Applied Energy Journal* (In press).

Articles under review

1. **R. Ahshan**, M. T. Iqbal, George K. I. Mann, "Voltage regulation during off-grid operation of a small grid connected wind turbine," *Renewable Energy Journal*.

Bibliography

[1] R. Hoffmann and P. Mutschler. The influence of control strategies on the energy capture of wind turbines. *Industry Applications Conference*, 2:886–893, Oct 8-12 2000.

[2] Siegfried Heier. *Wind Energy Conversion Systems.* Wiley, 1996.

[3] J. Gilbert, T. Forsyth, and P. Tu. Economics of grid-connected small wind turbines in the domestic markets. AWEA wind power conference, June 22-23 1999.

[4] Anders Grauers. Efficiency of three wind energy generator systems. *IEEE transactions on Energy Conversion*, 11(3), September 1996.

[5] W. Leithead, S. de la Salle, and D. Readon. Wind turbine control objectives and design. pages 510–515. European Community Wind Energy Conference, September 1990.

[6] A.D. Simmons, L. L. Freris, and J. A. M. Bleijs. Comparision of energy capture and structural implications of various policies of controlling wind turbines. pages 99 103, Amsterdam, 1991. EWEC.

[7] P. Mutschler and R. Hoffman. Comparision of wind turbines regarding their energy generation. volume 1, pages 6–11, Cairns, Qld., Australia, June 23-27 2002. 33rd Annual IEEE Power Electronics Specialists Conference.

[8] M.T. Iqbal. Modeling and simulation of a small wind turbine. St. John's, NL, November 12 2003. IEEE Newfoundland Electrical and Computer Engineering Conference.

[9] J. T. Bialasiewicz. Furling control for small wind turbine power regulation. pages 804 809. International Symposium on Industrial Electronics, 2003.

[10] E. Muljadi, T. Forsyuth, and C.P. Butterfield. Soft-stall control versus furling control fro small wind turbine power regulation. Technical Report CP 500-25100., NREL, July 27 1998.

[11] Q. Wang and L Chang. An intelligent maximum power extraction algorithm for inverter based variable speed wind turbine systems. *IEEE Transactions on Power Electronics*, 19(5):1242 1249, September 2004.

[12] M. Ermis, H. B. Ertan, E. Akpinar, and F. Ulgut. Autonomous wind energy conversion system with a simple controller for maximum-power transfer. volume 139. IEE Electronic Power Applications Proceedings, September 1992.

[13] T. Tanaka and T. Toumiya. Output control by hill-climbing method for a small wind power generating system. *Renewable Energy*, 12(4):387 400, 1997.

[14] J. H. Enslin and J. V. Wyk. A study of wind power converter with micro-computer based maximum power control utilizing an over-synchronous electronic scherbius cascade. *Renewable Energy*, 2(6):551–562, 1992.

[15] Enertech series 4000 installation and operation. Technical report, Enertech Corporation, 1980.

[16] Soenke Siegfriedsen. aerosmart5-the new generation of small wind energy converters (swec). Technical report, Aerodyn Energiesteme GmbH, Pro-vianthausstrasse 9, 24768 Rendsburg, Germany, October 2004.

[17] Small wind energy implementation strategy (swiis) consortium. Technical report, May 20 2005.

[18] Raymond M. Hudson, Tony Thome, Fereydoun Mekanik, Michael R. Behnke, Sigifredo Gonzalez, and Jerry Ginn. Implementation and testing of anti-islanding algorithms for ieee 929 - 2000 compliance of single phase photovoltaic inverters. *IEEE*, 0-7803-7471-1 /02, 2002.

[19] Ye. Zhihong, Amol Kolwalkar, and Vinod John. Investigation of anti-islanding protection of power converter based distributed generators using frequency domain analysis. *IEEE Transactions on Power Electronics*, 19(5):1177–1183, September 2004.

[20] J. Stevens, R. Bonn, J. Ginn, S. Gonzalez, and G. Kern. Development and testing of an approach to anti-islanding in utility-interconnected photovoltaic systems. Technical report, Sandia Report SAND, http://www.sandia.gov/pv/0800steve.pdf, August 2000-1939.

[21] G.A. Smith, P.A. Onions, and D.G. Infield. Predicting islanding operation of grid connected pv inverters. volume 147. IEEE Proc. Electrical Power Applications, January 2000.

[22] S.J. Huang and F.S. Pai. A new approach to islanding detection of dispersed generators with self-commuted static power converters. *IEEE Transactions on Power Delivery*, 15(2), April 2000.

[23] Michael Eugene Ropp. *Design issues for grid-connected photovoltaic systems.* Ph.d. dissertation, GeorgiaTech, October 12 1998.

[24] P. O'Kane and B. Fox. Loss of mains detection for embedded generation by system impedance monitoring. pages 95–98. International Conference on Developments in Power System Protection, March 25-27 1997.

[25] P.D. Hopewell, N. Jenkins, and A.D. Cross. Loss-of-mains detection for small generators. volume 143. IEE Proceedings of Electrical Power Applications, May 1996.

[26] Wei Gu, Jianxin Chu, and Shihong Gan. Starting performance research of a high-power middle-voltage induction motor soft starter based on the on-off transformer. Montreal, Quebec, Canada., July 9-12 2006. IEEE International Symposium on Industrial Electronics.

[27] M. Ayyub. Anfis based soft-starting and speed control of ac voltage controller fed induction motor. IEEE Power India Conference, April 10-12 2006.

[28] J. Wu, R. Zhao, and Z. Shang. The design of soft starter for ac motors based on single neuron pi regulator. volume 1, pages 3009 3013. Intelligent Control and Automation, June 21-23 2006.

[29] S. A. Qurashi and A.R. Kashif. Starting techniques of induction motors and development of low cost soft starters. *IEEE*, 53:31–40, July - September 2006.

[30] A. Gastli and M.M. Ahmed. Ann-based soft starting of voltage controlled fed im drive system. *IEEE Transactions on Energy Conversion*, 20(3):497-503, September 2005.

[31] D. Gritter, D. Wang, and Habetler. Soft starter inside delta motor modeling and its control. volume 2, pages 1137 – 1141. IEEE Industry Applications Conference, October 8-12 2000.

[32] A. J. J. Reek, CAD. Coelho, JA. Cortez, J.M.E. Vicente, J.P.G.Abreu, C.D.Ramos, C. Magallhaes, and V.F. da Silva. Energy conservation with use of softstarter. 0- 7833-6499-6/ 2000 IEEE.

[33] B. Lemström, J. Räkköläinen, , and E. Peltola. A wind farm's impact on the quality of electricity in a weak network. pages 747–749, Nice, France, Mar. 1-5 1999. European Wind Energy Conference.

[34] G. Gerdes, F. Santjer, and R. Klosse. Overview and development of procedures on power quality measurements of wind turbines. pages 716–721, Dublin, Ireland, October 1997. European Wind Energy Conference.

[35] A. Larsson. Guidelines for grid connection of wind turbines. Nice, France, June 1-4 1999. 15th Int. Conf. on Electricity Dist.

[36] Draft IEC 61 400-21: Power Quality requirements for Grid Connected Wind Turbines. Committee Draft (CD) 1998-12-11. Technical report, International Electro- technical Commission.

[37] T Ackermann. *Wind Power in Power Systems*. ISBN, 0-470-85508-8. J. Wiley and Sons, 2005.

[38] F. Iov, Hansen, F. Blaabjerg, and Remus Teodorescu. Modeling of soft-starters for wind turbine applications. pages 179–182. Power quality proceedings, May 2003.

[39] F. Iov, F. Blaabjerg, Zhe Chen, A. D. Hansen, and P. Sørensen. A new simulation platform to model, optimize and design wind turbines. *0-7803-7474-6/02 IEEE*, pages 561–566, 2002.

[40] Ion Boldea Lucian Mihet-Popa, Frede Blaabjerg. Wind turbine generator modeling and simulation where rotational speed is the controlled value. *IEEE transactions on industry applications*, 40(1), January/February 2004.

[41] Torbjorn Thiringer. Grid-friendly connecting of constant-speed wind turbines using external resistors. *IEEE transactions on energy conversion*, 17(4), December 2002.

[42] Ammasaigounden N. and M. Subbiah. Chopper-controlled wind-driven self-excited induction generators. *IEEE Transactions on Aerospace and Electronic Systems*, AES-25(2), March 1989.

[43] M. Juan, Ramirez, and M. Emmanuel Torres. An electronic load controller for the self-excited induction generator. *IEEE Transaction on Energy Conversion*, 22(2), June 2007.

[44] B. Singh, S. S. Murthy, and S. Gupta. Analysis and implementation of an electronic load controller for a self excited induction generator. volume 151. IEEE Proceedings in Gener. Transm. Distrib., January 2004.

[45] B. Singh, S. S. Murthy, and S. Gupta. Analysis and design of electronic load controller for self-excited induction generators. *IEEE Transactions on Energy Conversion*, 21, March 2006.

[46] Tarek Ahmed, Koki Ogura, Koji Soshin, Eiji Hiraki, and Mutsuo Nakaoka. Small-scale wind turbine coupled single-phase self-excited induction generator with svc for isolated renewable enery utilization. Technical report, The graduate School of Science and Engineering, Yamaguchi University, Japan.

[47] Md. Arifujjaman, M.T. Iqbal, and John E. Quaicoe. A novel small wind turbine emulator. St. John's, NL, November 2005. 15th IEEE Newfoundland Electrical and Computer Engineering Conference.

[48] F. A. Farret, R. Gules, and J. Marian. Micro-turbine simulator based on speed and torque of a dc motor to drive actually loaded generator. pages 89–93. First IEEE International Caracas Conference, December 12-14 1995.

[49] L. Chang, R. Doraiswami, T. Boutot, and H. Kojabadi. Development of a wind turbine simulator for wind energy conversion system. pages 550–554. 0-7803-5957-7/00 IEEE, 2000.

[50] H. M. Kojabadi, L. Chang, and T. Boutot. Development of a novel wind turbine simulator for wind energy conversion systems using an inverter-controlled induction motor. *IEEE Transactions on Energy conversion*, 19(3):547–552, September 2004.

[51] H. M. Kojabadi and Liuuchen Chang. A novel steady state simulator using an inverter controlled induction motor. *Wind Engineering*, 28(4):433–446, 2004.

[52] Lu. Jian, Xu. Cheng, and Wang. The simulation system of wind turbine performance using a microcontroller controlled scr dc motor. pages 865–868. BICEM Paper, August 1987.

[53] Nunes, Alexandre Augusto Cancado Seixas, Paulo Fernando Cortizo, Profirio Cabaleiro Silva, and Selenio Rocha. Wind turbine simulator using dc machine and power reversible converter. pages 536–540, Adelaide, Australia, September 14-16 1993. ICEMA.

[54] Rodriguez-Garcia J. L. Burgos J. C. Chinchilla M. Arnalte S. Veganzones C. Rodriguez-Amenedo, J. L. Experimental rig to emulate wind turbines. volume 3, pages 2033–2038, Istanbul. Turkey, September 2-4 1998. ICEM.

[55] W. Rabelo, B. andHofmann and M. Gluck. Emulation of the static and dynamic behaviour of a wind turbine with a dc machine drive. volume 3, pages 2107 2121. Power Electronics Specialists Conference, 2004.

[56] P. E. Battaiotto, R. J. Mantaz, and P. F. Puleston. A wind turbine simulator based on dual dsp processor system. *Control Engineering Practice*, 4(9):1261 1266, 1996.

[57] D. Diop, C. Nichita, J. J. Belhache, B. Dakyo, and E. Ceanga. Modeling variable pitch hawt characteristics for a real time wind turbine simulator. *Wind Engineering*, 23(4):225 243, 1999.

[58] F. Barrero, J. L. Mora, M. Perales, A. Marachante, E. Galvan, J. M. Carrasco, A. Torralba, and L. G. Franquelo. A test-ring to evaluate a wind turbine generation control system based on dsp. ISBN 90-75815-02-6, Trondheim, Noruega, Septiembre de 1997. European Conference on Power Electronics and applications.

[59] Luiz A. C. Lopes, Josselin Lhuilier, Avishek Mukharjee, and Mohammad F. Khokhar. A wind turbine emulator that represents the dynamics of the wind turbine rotor and drive train. *0-7803-9033-4/05 IEEE*, (2092-2097), 2005.

[60] Paul Gipe. Wind power for home and business: Renewable energy for the 1990s and beyond. White River Junction, Vermont, Totnes, England.

[61] Nichita Cristian, D. Amadou Diop, Jean J. Belhache, Brayima Dakyo, and Ludovice Protin. Control structure analysis for a real time wind system simulator. *Wind Engineering*, 22(6), 1998.

[62] J. F. Manwell, J. G. McGown, A. Rogers, and W. Stein. Developments in experimental simulation of wind/diesel systems. Glasgow, Scotland, July 1989. European Wind Energy Conference.

[63] J.T.G. Pierik, M. J. Hoeijmakers, J. M. Vleeshouwers, T. G. Van Engelen, C. W. A. Baltus, A. T. Veltman, and A. Warmenhoven. A variab le speed system with integral control for wind turbines(irflet): Design of the test-rig. Technical report, Amsterdam, 1991.

[64] M. T. Iqbal. A small induction generator based grid connected wind turbine simulator. St. Joh's, NL, November 2005. 15th IEEE Newfoundland Electrical and Computer Engineering Conference.

[65] Electricity, electricity feed laws, feed-in tariffs, and advanced renewable tariffs. Technical report, www.wind-works.org/articles/feedlaws.html, Last accessed June 6 2007.

[66] M. P. Papadopoulos, S. A. Papathanassiou, N. G. Boulaxis, and S. T. Tentzerakis. Voltage quality change by grid-connected wind turbine systems. pages 783–785, Nice, France, 1999. European Wind Energy Conference.

[67] T. Petru and T. Thiringer, editors. *Active Flicker reduction from a sea-based 2.5 MW wind park connected to a weak grid*, Aalborg, Denmark, June 13-16 2002. Proceedings Nordic Workshop on Power and Industrial Electronics.

[68] F. Castro Sayas and R. N. Allan. Generation availability assessment of wind farms. volume 143. IEEE Proceedings-Gener. Trans. Distrib., September 1996.

[69] E. Welfonder, R. Neifer, and M. Spanner. Development and experimental identification of dynamic models for wind turbines. *Control Engineering Practice*, 5(1):63–73, 1997.

[70] B. S. Borowy and Z. M. Salameh. Dynamic response of a stand-alone wind energy conversion system with battery energy storage to a wind gust. *IEEE Transactions on Energy Conversion*, 12(1), March 1997.

[71] Remus Teodorescu, Florin Iov, and Frede Blaabjerg. Flexible development and test system for 11 kw wind turbine. *0-7803-7754-0/03, IEEE*, 2003.

[72] C. C. Johnson and R. T. Smith. Dynamics of wind generators on electric utility networks. *IEEE Transactions On Aerospace and Electronic Systems*, AES-12(4):483–492, July 1976.

[73] K. Ogata. *Modern Control Engineering*, 4 edition, 2002.

[74] MAWDSLEY'S LTD, Dursley, Gloucestershire, England. *The Multiform Experimental Sets Manual*, January 1967.

[75] Stefan Soter and Ralf Wegener. Development of induction machines in wind power technology. Technical report, Institute of Electrical Drives and Mechatronics, University of Dortmund, Germany.

[76] Mohamed Orabi, M. Z. Youssef, and P. K. Jain. Investigation of self-excited induction generators for wind turbine applications. *0-7803-8253-6/04 IEEE*, 2004.

[77] M. P. Jain S. P. Singh and Bhim Singh. A new technique for analysis of self-excited induction generator. *Electric Machine and Power Systems*, 23:647–656, 1995.

[78] L. Shridhar, B. P. Sineh, and C. S. Jha. A step towards improvements in the characteristics of self-excited induction generator. *IEEE Transactions on Energy Conversion*, 8(1):40–46, March 1993.

[79] Dawit Seyoum, Colin Grantham, and Muhammed Fazlur Rahman. The dynamic characteristics of an isolated self-excited induction generator driven by a wind turbine. *0093-9994/03 IEEE*, 2003.

[80] Standards Coordinating Committee 21. *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.* The Institute of Electrical and Electronics Engineers, Inc., 3 Park Avenue, New York, July 28 2003.

Appendix A

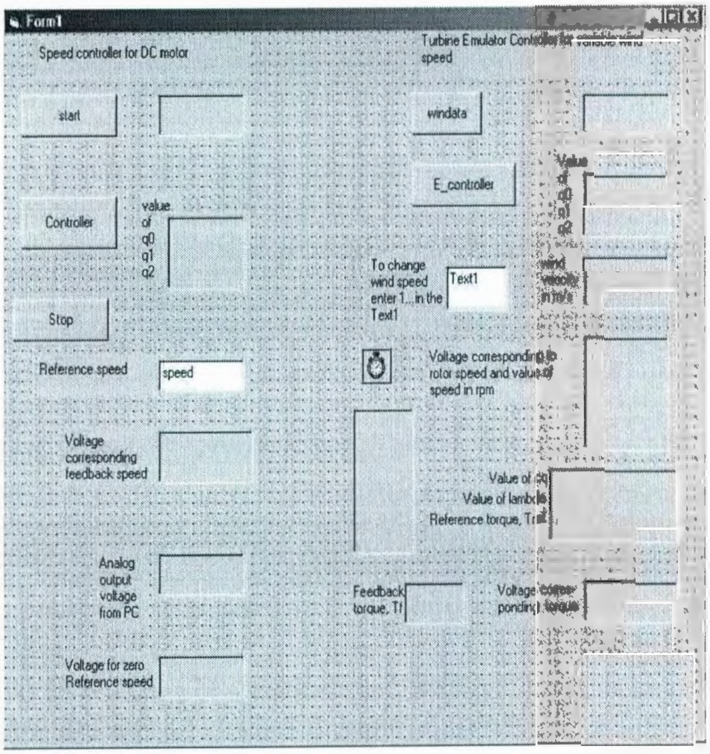


Figure 6.1: Wind turbine simulator implementation in visual basic environment

```
Private Declare Function GetTickCount Lib "kernel32" () As Long


''To start the machine at a reference speed.

Private Sub Command3_Click()

Dim j As Single
Dim k As Single
For j = 1 To 220
v = 1 + (j / 100)

For k = 1 To 5000000
Next k

Picture3.Cls
Picture3.Print v
```

```
Chan% = 0             ' output channel
Const Range% = UNI5VOLTS
AO_data = Val(v)    'Data range 0-4095
DataValue% = (v / 5) * 1023
ULStat% = cbFromEngUnits(0, Range%, AO_data, DataValue%)
If ULStat% <> 0 Then Stop
ULStat% = cbAOut(0, Chan%, Range%, DataValue%)
If ULStat% <> 0 Then Stop
Next j
End Sub

'Wind turbine simulator code

Private Sub Command5_Click()

'Variable declaration

Dim v As Single
Dim e1 As Single
Dim e2 As Single
Dim e3 As Single
Dim u1 As Single
Dim u2 As Single
Dim vi As Single
Dim vit As Single
Dim vo As Single
Dim v1 As Single
Dim i As Single
Dim t As Single
Dim ti As Single
Dim td As Single
Dim t0 As Single
Dim q0 As Single
Dim q1 As Single
Dim q2 As Single
Dim power As Single

Dim current As Single
Dim w(1 To 8) As Single


Dim c(1 To 8) As Single

Dim delay As Integer
Dim delay1 As Integer
Dim k As Integer
```

```
Dim P As Integer
Dim u(1 To 8) As Single


'Files open to write output variables

Open "filesVs" For Output As #2
Open "filesspeed" For Output As #3
Open "filescurrent" For Output As #4

'Initial conditions and sampling time for simulator controller

t1 = 0
t0 = 0.03995
e1 = 0: e2 = 0: e3 = 0
u2 = 2.9

'Simulator controller parameter selection

kp = 0.077
ti = 8.6
td = 0
q0 = kp * (1 + (td / t0))

q1 = kp * ((t0 / ti) - (2 * (td / t0)) - 1)
q2 = kp * (td / t0)
Picture12.Cls
Picture12.Print q0
Picture12.Print q1

Picture12.Print q2

'Wind profile file

P = 1
Open "winddata" For Input As #1
10  Input #1, w(P)
c(P) = w(P)
Picture6.Cls
Picture6.Print c(P)

'Calculation of wind turbine torque by taking wind data

pi = 3.14
R = 1.25
x = R / (2.6 * 9.549)
u(P) = Val(c(P))
```

```
a = u(P)
ad = 1.2929
lTimer = GetTickCount
For i = 1 To 8000

If i >= 1 And i <= 7500 Then

Gain = BIP10VOLTS                                   ' set the gain
Chan% = 3                                            ' set input channel
ULStat% = cbAIn(0, Chan%, Gain, DataValue%)
vi = (20 * (DataValue% / 4095) - 10)
Gain = BIP10VOLTS                                  ' set the gain
Chan% = 2                                          ' set input channel
ULStat% = cbAIn(0, Chan%, Gain, DataValue%)
current = (20 * (DataValue% / 4095) - 10)
speed = (154.17 * vi) + 1358.2 'Input calibration equation for speed

t1 = t1 + t0
Write #3, speed, t1
Write #4, current, t1
Picture7.Cls
Picture7.Print vi
Picture7.Print speed
lambda = (speed * x) / a

cq = (-0.02812) + (0.038576 * lambda) - (0.0045912 * lambda ^ 2) +
(0.0001489 * lambda ^ 3)

Tref = (0.5 * ad * u(P) ^ 2 * pi * R ^ 3 * cq) / 2.6 Picture8.Cls
Picture8.Print cq
Picture8.Print lambda
Picture8.Print Tref

' Feedback torque calculation

Gain = BIP10VOLTS                              ' set the gain
Chan% = 1                                      ' set input channel
ULStat% = cbAIn(0, Chan%, Gain, DataValue%)
vit = (20 * (DataValue% / 4095) - 10)
Picture10.Cls
Picture10.Print vit

Tf = (vit - 0.28) * 1.4546 'Input calibration equation

Picture9.Cls
Picture9.PrintTf
e1 = e2
```

```
e2 = e3

e3 = (Tref - Tf) 'error in torque

u1 = u2 u2 = u1 + (q0 * e3) + (q1 * e2) + (q2 * e1)
v1 = u2

If v1 < 2.9 Or v1 > 4.15 Then
vo = 2.9
Else vo = v1
End If
Picture2.Cls
Picture2.Print vo
Chan% = 0             ' output channel
Const Range% = UNI5VOLTS
AO_data = Val(vo)    'Data range 0-4095
DataValue% = (vo / 5) * 1023
ULStat% = cbFromEngUnits(0, Range%, AO_data, DataValue%)
If ULStat% <> 0 Then Stop
ULStat% = cbAOut(0, Chan%, Range%, DataValue%)
If ULStat% <> 0 Then Stop
t = t + t0
Write #2, Tref, Tf, t
Else P = P + 1
If P <= 8 Then

GoTo 10

Else
End If
End If

Next i

Debug.Print "Timer Taken:" & GetTickCount - lTimer Close End Sub

Private Sub tmrReadCount_Timer()

Picture13.Print Time$

End Sub
```

Appendix B

Control code while disconnection decision is taken based on current and speed measurement.

```
’Program current measurement

dim volt_gen as word
dim volt_grid as word
dim current_1 as word

dim current as word
dim sp_data as word
dim vol_speed as word

dim speed as word
dim fre_gen as word
dim fre_grid as word
main:
TRISA  = %11111111         ’ PORTA is input
TRISB  = %00000000         ’ PORTB is output
ADCON1 = %1000010          ’0 and 5V are reference voltage values
again:
  clearbit(PORTB,0)
  clearbit(PORTB,2)
  Delay_ms(10000)
  Delay_ms(10000)
  volt_gen = ADC_read(3)’Execute conversion and store result in variablevolt_gen.
  volt_grid = ADC_read(5)’Execute conversion and store result in  variable volt_gri
  current = ADC_read(0)
  sp_data= ADC_read(2)
  fre_gen=ADC_read(4)
  fre_grid= ADC_read(7)

if (volt_gen >= 367)and(volt_grid>=206) then   ’check the grid
connection condition
   if (fre_gen >= 615)and(fre_grid>=640) then
     Delay_ms(3000)
     setbit(PORTB,0)                  ’ turn on relay1
     clearbit(PortB,2)                ’after 2ms turn off  relay1 and on relay2
     Delay_ms(2000)
     clearbit(PortB,0)
     aloop:
     setbit(PORTB,2)
     Delay_ms(10000)
     Delay_ms(10000)
     Delay_ms(10000)
   else
```

```
     bloop:
     clearbit(PORTB,2)
     clearbit(portB,0)
     Delay_ms(10000)
     Delay_ms(10000)
     Delay_ms(10000)
     Delay_ms(10000)
     goto again
 end if
else
   goto again
end if
  volt_gen = ADC_read(3)
  volt_grid = ADC_read(5)
  current = ADC_read(0)
  current_1 = (current+41)
  sp_data = ADC_read(2)
  vol_speed=(sp_data/205)
  speed=(154*vol_speed+1359)
  fre_gen=ADC_read(4)
  fre_grid= ADC_read(7)
  if (speed <1790) then
     if (current_1> 256)and(current_1<291) then
      Goto bloop
     else
      Goto aloop
     end if
else
    Goto aloop
end if
end.
```

Appendix C

Control code while disconnection is done based on power measurement

```
'Program power_measure

dim volt_gen as word
dim volt_grid as word
dim power as word

dim fre_gen as word
dim fre_grid as word
main:
TRISA  = %11111111       ' PORTA is input
TRISB  = %00000000       ' PORTB is output
ADCON1 = %1000010        ' 0 and 5V are reference voltage values
again:
  clearbit(PORTB,0)
  clearbit(PORTB,2)
  Delay_ms(10000)
  Delay_ms(10000)
  volt_gen = ADC_read(3)'Execute conversion and store result in variable volt_gen.
  volt_grid = ADC_read(5)'Execute conversion and store result in variable volt_grid
  fre_gen=ADC_read(4)
  fre_grid= ADC_read(7)

  if (volt_gen >= 367)and(volt_grid>=206) then
    if (fre_gen >= 615)and(fre_grid>=640) then        'check the grid connection co
     Delay_ms(2000)
     setbit(PORTB,0)                                    ' turn on relay1
     clearbit(PortB,2)                                  'after 450 ms turn off 'rel
     Delay_ms(450)
     clearbit(PortB,0)
     aloop:
     setbit(PORTB,2)
     Delay_ms(10000)
     Delay_ms(10000)
     Delay_ms(10000)
    else
   bloop:
     clearbit(PORTB,2)
     clearbit(portB,0)
     Delay_ms(10000)
     Delay_ms(10000)
     Delay_ms(10000)
     Delay_ms(10000)
```

```
      goto again
    end if
  else
    goto again
    end if
  power = ADC_read(1)
      if (power< 386) then
        Goto bloop
      else
        Goto aloop
      end if
end.
```

Appendix D

Control code to detect grid failure and switch over the system in off-grid mode

```
'program off_grid mode

dim volt_gen as word
dim volt_grid as word
dim power as word dim
fre_gen as word
dim fre_grid as word
main:
TRISA  = %11111111       ' PORTA is input
TRISB  = %00000000       ' PORTB is output
ADCON1 = %1000010        ' 0 and 5V are reference voltage values
again:
  clearbit(PORTB,3)
  clearbit(PORTB,0)
  clearbit(PORTB,2)
  Delay_ms(10000)
  Delay_ms(10000)
  volt_gen = ADC_read(3)'Execute conversion and store result  in variable volt_gen.
  volt_grid = ADC_read(5)'Execute conversion and store result in  variable volt_gri
  fre_gen=ADC_read(4)
  fre_grid= ADC_read(7)
 if (volt_gen >= 367)and(volt_grid>=206) then
     if (fre_gen >= 615)and(fre_grid>=640) then 'check the grid connection conditio
     Delay_ms(2000)
     setbit(PORTB,0)
     clearbit(PortB,2)
     Delay_ms(450)
     clearbit(PortB,0)
     aloop:
     setbit(PORTB,2)
     Delay_ms(10000)
     Delay_ms(10000)
     'Delay_ms(10000)
     else
   bloop:
     clearbit(PORTB,2)
     clearbit(portB,0)
     Delay_ms(10000)
     Delay_ms(10000)
     volt_grid = ADC_read(5)
       if (volt_grid>170) then
         goto again
          else
```

```
         goto cloop
       end if
    end if
 else
   goto again
 end if
 power = ADC_read(1)
      if (power> 390) then
      Goto aloop
      else
      Goto bloop
      end if
    cloop:
    clearbit(PORTB,2)
    clearbit(portB,0)
    setbit(PORTB,3)
    volt_grid = ADC_read(5)
     if (volt_grid>170) then
       Goto again
     else
       Goto cloop
     end if
end.
```