REMOTE CONTROL OF DISTRIBUTED GENERATION SYSTEM

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Remote Control of Distributed Generation System

by

© Farhana Shirin Lina BSc., (Electrical and Electronic)

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Engineering

Faculty of Engineering and Applied Science
Memorial University of Newfoundland

November, 2009

St. John's **Newfoundland** **Canada**

ABSTRACT

The dynamic nature of distributed generation (e.g. from wind) makes to design a control system for wind turbines that utilize wind energy. The design of a wind turbine control system becomes more difficult when the system is operated in grid-connected mode. The major issues include connection standard, control system complexity, cost and required instrumentation. A low cost control system and its associated instrumentation development is very important for commercial success of a small grid connected inverter based wind turbine. The proposed grid connected inverter based remote control system is a good candidate for distributed generation system such as a small wind turbine.

The main purpose of this research is to present a novel remote power control for a small single phase grid connected inverter using a DC-DC converter and an ADR101 serial data acquisition card. Before grid connection characteristics of the inverter are programmed for a desired input DC voltage for generating the output electrical power. Input dc voltage of the inverter is adjusted by controlling the DC-DC converter. A PC is employed to receive the required output power signal from a dispatch center via the Internet. The PC determines the power being fed by the inverter to the grid and uses an ADR101 to control the dc-dc converter to adjust the power flow to the grid.

The performance of the developed control system investigated both in simulation and experiment. DC power supply is used at generation side and inverter output at grid side is adjusted based on an existing data file in PC. A PI controller is designed which makes sure that power flow is always the same as required by the electrical power dispatch center.

The applicability of the proposed remote control system based on a 250 watts grid connected inverter is demonstrated through a number of lab tests. The results show the designed control system is capable of remotely controlling the system power of the grid tie inverter.

Acknowledgements

This work has been carried out at the Faculty of Engineering & Applied Science at Memorial University of Newfoundland, Canada. It has been funded by Atlantic Innovation Fund Canada and School of Graduate Studies (SGS) of Memorial University. I am obliged to express my gratitude to those organizations providing me financial support during my course program.

Also, my gratitude goes to my supervisor Dr. M. Tariq Iqbal for his supervision and guidance throughout my master's work. His positive attitude, support, encouragement and scientific reviewing made me more confident to carry out my research successfully. I am really grateful and admirable to him.

I would also like to thank all the fellow members of the Centre for Instrumentation, Control and Automation (INCA), Energy system lab at Memorial University for providing a good working environment.

I am highly indebted to my mother Nila Chowdhury, my father Jafar Ullah Chowdhury and my sisters for their continuous supports. Special thanks to my loving husband Md. Khaled Hassan Chowdhury for his continuous support and guidance throughout the program.

I would like to dedicate this work to our new born daughter Sarah Hassan.

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List of Symbols

$Q\text{-}V$	Reactive power-Voltage
V_m	Maximum voltage
$V_{m,ref}$	Reference voltage
PI	Proportional Integral controller
P	Proportional controller
Q_m	Reactive power
V_β	Single phase voltage
V_a	Internally generated signal
$\alpha\beta\text{-}dq$	Park transformation block
d	d-axis
q	q-axis
K_p	Proportional gain
K_i	Integral gain
$I\text{-}V$	Current-Voltage
V_{out}	Analog output voltage
I_p	Primary current
I_{PN}	Primary nominal RMS current
V_{con}	Control voltage
$G_1(S)$	Transfer function for DC-DC converter
$G_2(S)$	Transfer function for inverter converter
$G_{DC}(S)$	DC gain for DC-DC converter
τ	Time constant
G_{AC}	Gain for Inverter
I_{Grid}	Grid current
V_{in}	Input voltage
I_{ref}	Reference current
W_{grid}	Supplied power to the grid
V_{AC}	Phase voltage

List of Abbreviations

DG	Distributed Generation
EPRI	Electric Power Research Institute
CO_2	Carbon di-Oxide
NO_x	Nitrogen Oxide
SO_x	Sulfur Oxide
GW	Giga Watt
KW	Kilo Watt
MW	Mega Watt
PCU	Power Conditioning Units
DC	Direct Current
AC	Alternating Current
MPPT	Maximum Power Point Tracking
PLL	Phase Locked Loop
DSP	Digital Signal Processor
ICC	Intelligent Cluster Controller
SPWM	Signal Pulse Width Modulation
K Hz	Kilo Herz
CCU	Central Control Unit
OLTC	On Load Tap Changer
FC	Fuel Cell
PV	Photo Voltaic
NPC	Neutral Point Clamped
ADR	Analog/Digital/RS232
PID	Proportional, Integral, Derivative
DNO	Distribution Network Operator
PWM	Pulse Width Modulation

PCC	Point of Common Coupling
PIC	Peripheral Interface Controller
CPU	Central Processor Unit
DAC	Digital to Analog Converter
LED	Light Emitting Diode
mA	Mili Ampere
m.sec	Mili Second
AN_0	Analog Port 0
PA_0 to PA_7	Port A_0 to Port A_7
TCP	Transmission Control Protocol
IP	Internet Protocol
PEC	Power Electronic Converter

Chapter 1: Introduction and literature review

1.1 Introduction

There are two components in the electricity supply system, which are the electrical power generation and the electrical power distribution to various load. The conventional power generation part is usually synchronous-generator that mechanical power into electrical power or a device that can convert solar or wind powers into electrical power [1]. In the case of large generators electrical connections will include a transmission network and a distribution network. Electrical connection between energy converter and transmission lines may be direct or through an inverter.

The term of distributed generation (DG) (also called decentralized energy [2]) or distributed energy is a method of generating electricity from numerous small sources, such as photovoltaic, fuel cells, wind turbines etc. that are close to the point of electrical power delivery. It is expected that distributed generation will be common in future's power systems as a result of the beginning of competition in the electric industry along with the increased demand to generate electricity from environmentally friendly resources. The concept of distributed generation was (re)introduced by the Electric Power Research Institute (EPRI) in the early 1990s. EPRI defines distributed generation as "the integrated or standalone use of small modular resources by utilities, utility customers and third parties in applications that benefit the electric system, specific customers or both" [3]. A number of other definitions have been formulated in the literature (e.g. [4,5]) as well leading to some confusion. Therefore, a general definition for distributed generation was suggested recently in [6]. It has been defined there as "electric power generation within the distribution network or on the customer side of the network." An example of a future power system with different types of distributed generation, including some form of energy storage, is shown in Figure 1.1.

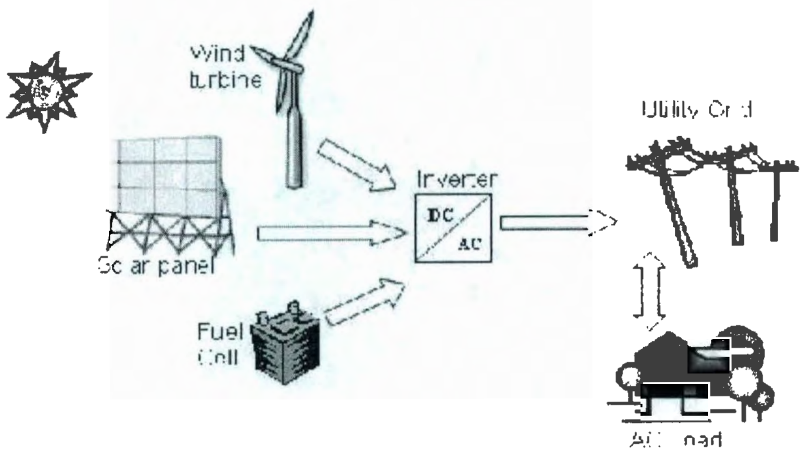

Fig.1.1: Example of a future power system with distributed generation

(http://fec.eng.monash.edu.au/2005)

Distributed generation reduces power losses in distributing and delivering electric power because the electric power is usually generated close to delivery points. It also reduces the number of power lines that have to be constructed. In general, power electronic interfaces are required to connect distributed generation units with the utility grid. State-of-the-art power electronic interfaces usually comprise a voltage source inverter to establish a DC to AC conversion.

DG became almost extinct in the period before 1990. The primary reason for this was that the economies gained by building larger power stations outweighed the additional costs of transporting the electricity to consumers. In 1993 and 1994 there was just 1.2GW of distributed independent generation in England and Wales and $107X10^6$ GW energy consumed from non-renewable energy sources. Distributed independent generation has grown to over 12GW today [7]. The Energy Networks Association now collects data on DG activity and publishes it quarterly on its website [8]. The fundamental benefit of DG remains that it promises significant reductions in electrical power distribution and delivery cost. The precise potential for efficiency gains and emissions savings varies depending on the generation technology and the location of the generation unit. Modern society widely depends on fossil energy that speeds up global warming by emitting environmental pollutants such as CO_2, NO_x, SO_x gases, etc. Renewable energy is a good remedy to decrease environmental problems resulting from fossil energy. Renewable energy generation systems range from 1 kW to several hundred MW levels which are normally connected to a main power grid as a distributed generation (DG) system [9]. Technologies using renewable energy sources often need to be located distantly from consumers to take advantage of localized energy resources. In general, as smaller generation technologies reduce their capital and operating costs compared with larger generators their distribution and delivery benefits will encourage their further growth. There are a number of DG technologies. Some are tried and tested but others are new developing technologies. DG technologies include fossil-fuelled devices as well as those that use renewable fuels. Small DG technologies in the range of 100kW such as wind turbines, photovoltaic and fuel cells are currently gaining wide interest. Low cost power conditioning units (PCU) serve as interfaces between the distributed energy source and the grid [10]. The PCU conditions the source energy appropriately to meet the grid requirements. Indeed a PCU forms an integral part of any distributed generation system. The operation of a PCU depends upon the voltage magnitude and characteristics of the source being interfaced to the grid. Depending on the voltage level, the PCU may be required to "buck" or "boost" the available DC voltage to meet the grid voltage requirements. In addition to this, it should also condition the available DC power into high quality AC required to perform specific functions such as reactive power control [11] and maximum power point tracking [12]. Depending on the number of power stages used, a PCU may be a single or multistage configuration. Multistage PCUs offer a higher degree of freedom (more control variables), enabling easy implementation of several control functions (e.g. MPPT, reactive power compensation, active power filtering, etc.). For inverter-based distributed generation systems the inverters are connected to the existing grid; therefore, the voltage cannot be controlled. [13].

This research focuses on the remote control of inverter based distributed generation. As many distributed generation systems are connected to the grid through inverters, these need to be controlled to maintain a stable grid. Controlling the associated grid tie inverter can control the output power fed by a distributed generation system to the grid.

1.2 Literature Review

A small directly grid connected system with higher efficiency does not require complex power electronics for its control. The power electronic technology plays a vital role to meet the requirements of power quality, including: frequency, voltage, control of current, active and reactive power, harmonic minimization etc. The power systems consisting of the distributed generation units may have frequency and voltage control problems. However, the realization of control strategy for grid connection operation in different real-time situations is very important and further research is required to improve controlling performance.

According to past research, a proper control system make the distributed generation more reliable. A proper reactive power control of grid connected distributed generation will cause no extra pressure on the DG system. The system voltage control plus a Q-V droop regulation [14] is shown in Figure 1.2, where the voltage-reactive power control is combined with the Q-V droop control. The system output voltage is closely related to reactive power; therefore the voltage control is implemented by regulating the reactive power generation. The voltage control follows a Q-V droop characteristic, i.e. the unit will adjust its reactive power generation on consumption to maintain its output voltage. Also, other generation units will change their reactive power generation in response to the system voltage variation. Eventually the system reactive power will arrive at a new steady state. Voltage – reactive power controller is implemented by proportional-integral (PI) controller.

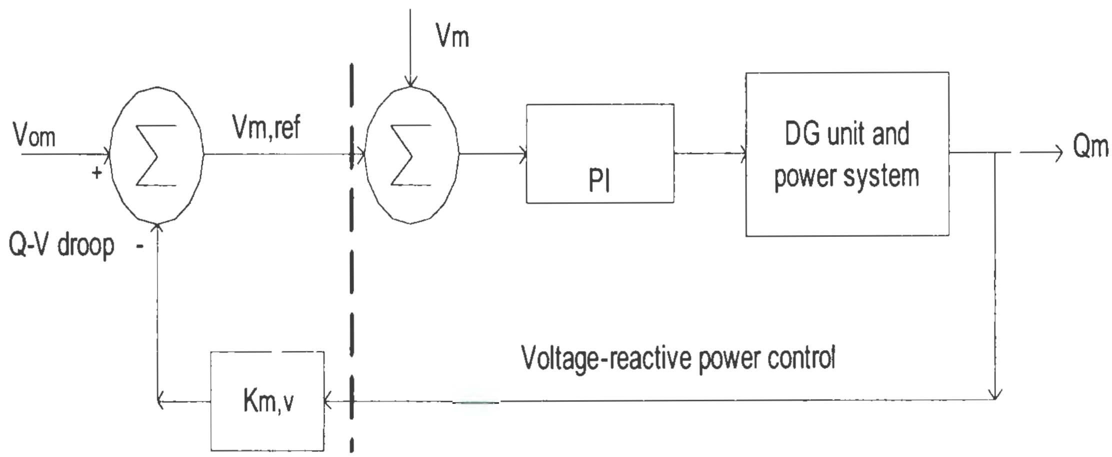

Fig.1.2: Q-V droop plus voltage-reactive power controller.

The DG control unit will control the system voltage by,

$$V_{m} = V_{om} - K_{m,v} Q_{m}$$

Where,

V_{om}= System voltage at unit power factor

Q_{m}= Reactive power

$K_{m,v}$ is the reactive power droop coefficient of the DG unit.

The reactive power of the unit has to be controlled to achieve the reference voltage. The current control technique and its implementation has been found in [15], [16]. By using resonant controllers [17] for both the current regulation in grid-connected control mode, as well as the voltage regulation in stand-alone control mode, zero steady-state error and fast transient response can be achieved. Resonant controllers are also used to implement selective harmonic compensation [18]. For connecting the DG system to the grid, a high-performance phase locked loop (PLL) structure for single-phase systems is presented with different ways. The PLL structure is implemented with a transport delay and an orthogonal filter. The transport delay is used to generate a virtual quadrature signal and the delay is adjusted in order to give a 90 degrees phase-shift with respect to the fundamental frequency of the input signal. A single phase voltage (V_β) and an internally generated signal (V_α) are used as inputs to a Park transformation block (αβ-dq). The *d*- axis output of the Park transformation is used in a control loop to obtain phase and frequency information of the input signal. V_α is obtained through the use of an inverse Park transformation, where the inputs are the *d* and *q*-axis outputs of the Park transformation (*dq-αβ*) fed through first-order pole blocks. The poles are used to introduce an energy storage element in the internal feedback loops. Figure 1.3 shows single phase PLL based on the use of a transport delay [19].

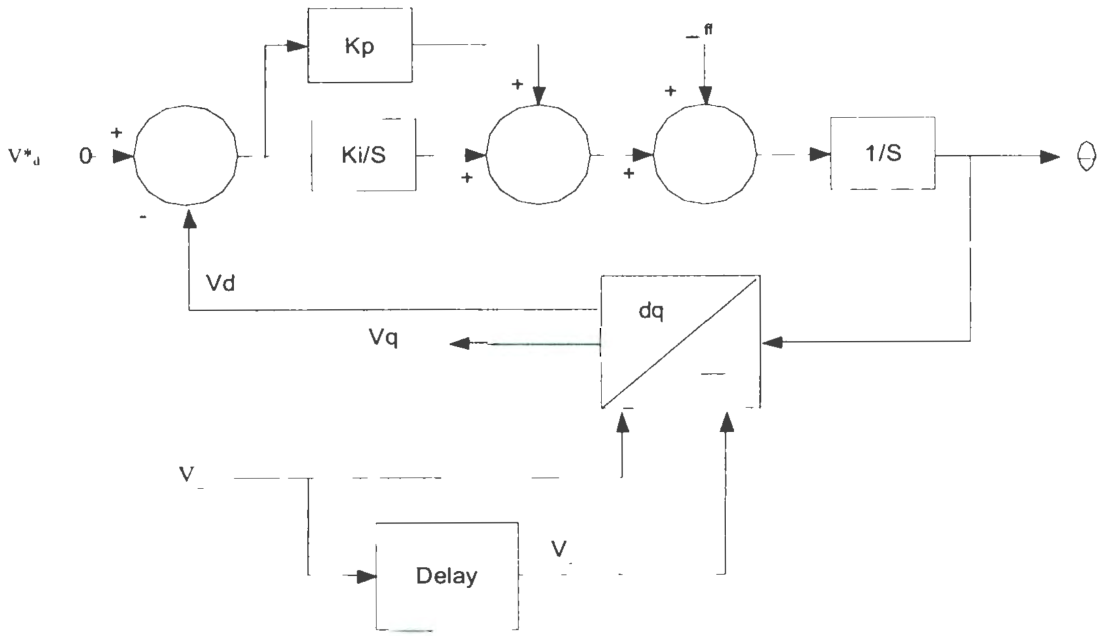

Fig.1.3: Single-phase PLL algorithm based on the use of a transport delay to generate the quadrature signal.

Orthogonal filter, which has been proposed for three-phase systems [20] (also referred as a multivariable filter), is employed for improving the PLL performance when the grid voltage is distorted. The operation of the system requires a real-time detection of grid status (such as outage, over/under-voltage and over/under-frequency). Zhang *et al.* [21] proposed a control method of grid connected string inverters based power plant. The power unit is controlled by a 32bit DSP (TMS320F2407) and intelligent cluster controller (ICC). The DSP operates grid current with SPWM working beyond the human audible frequency at 20 kHz, data communication and system protection has been executed. ICC monitors the operating status and data of each inverter. An interface control is responsible for controlling the DG active and reactive power output. It is most commonly designed to operate at unity power factor [22] to avoid interference with the voltage regulation devices connected on the utility side. For this reason a Central Control Unit (CCU) is implemented in order to manage and control the DG system. Comparative analysis of different voltage and reactive power control method in DG was presented in [23]. Both uncoordinated and coordinated voltage control, with and without DG involved in the voltage control, are investigated. The coordinated voltage control is presented based on automatic remote adjustment to the local operation of the voltage and reactive power equipment in the distribution system. The adjusted equipment includes the on-load tap-changer (OLTC), capacitors in the sub-station, and DG. The automatic adjustment is based on wide area coordination, in order to obtain an optimum voltage profile and reactive power flow for a one- day-ahead load forecast and DG output planning. Power quality control of an inverter based DG system is presented in [24] combined with PLL, current control and power control strategies. This allows active and reactive power control while maintaining high quality output current and power. DC-DC converter can suitably control current voltage (I-V) characteristic of a Photo Voltaic (PV) array and of a Fuel Cell (FC).The I-V laws of the PV and the FC have been obtained by an appropriate modeling of the considered renewable sources. The control system was verified in numerical simulation and experimentally that the designed DC-DC converter is able to reproduce the electrical characteristics of the experimental generator both in steady state and transient conditions, due to either load or parameters variations [25].

Another DC-DC converter applied to a three three-level neutral-point-clamped (NPC) voltage source inverter has been found in [26]. The converter is able to convert a low DC voltage between the range of 100 V and 200V. The voltage is provided by PV arrays or wind turbine connected to an AC-DC power stage to a split DC bus which is suitable to feed a three level three-phase NPC inverter. It was considered that the inverter is driving a squirrel-cage induction motor loaded by a load torque proportional to the square of the speed. The main purpose is to supply typical rural loads, when the input DC voltage is provided by a renewable source. A simplified schematic diagram of the complete drive system is illustrated in Figure 1.4, where only one inverter phase leg is shown.

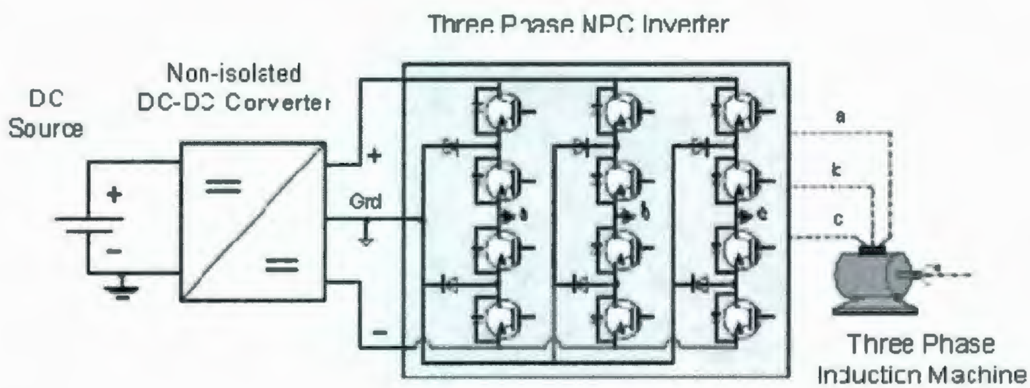

Fig.1.4: Three-level three-phase NPC inverter based motor drive system for renewable source applications (Felipe J. C. Padilha *et.al.* 2008)

A literature search indicates that a number of control techniques have been developed to control the DG system for various purposes. This research considers remote power control for DG system based on a grid connected inverter. Main objective is only active power control by controlling the DC link voltage.

1.3 Research Objectives

Evaluation of available literatures on recent developments of distributed generation system control reveals limitations associated with accuracy and performance. The main objective of this thesis is to develop a remote control of distributed generation system based on grid tie single phase inverter that provides improved control technique while enhancing the realism of the system. The following components that determine the effectiveness of remote control process will be addressed throughout the thesis: DC-DC converter that provides input rated voltage to the inverter. Data acquisition card, ADR101 controls the trim voltage of the dc-dc converter to control the power flow to the grid. A digital PID controller makes sure that power flow is always same as required by the electrical power dispatch center.

The electrical behavior of the grid tie inverter will be first studied and analyzed with the objective of gaining insight into the steady state and dynamic operating characteristics of the inverter. The feature obtained through study will be used to provide measurements of the inverter efficiency. The power converter topology selection and its control strategy will be addressed considering the experimental response of the ADR control algorithm. Effect of ultra capacitor storage in the DC link is also standard.

The main objectives of this thesis are to develope and demonstrate a low cost remote power control method for a small grid connected inverter. It is also required to demonstrate the applications of the developed method for distributed generation.

1.4 Thesis Outline

In chapter 2, system modeling and control for grid connected inverter are presented.

In chapter 3, the selection of system control, and its design and implementation issues are discussed. System simulation and control design are also presented.

In chapter 4, an experimental test result of remote control for inverter based DG is presented.

In conclusion, a summary of the research work in the thesis is presented. The outline of the contribution and achievement from this research work are also highlighted in chapter 5. The chapter also includes the recommendations for further investigations.

CHAPTER 2: SYSTEM MODELING AND CONTROL FOR GRID CONNECTED INVERTER

2.1 Introduction

In recent years, the small grid connected DG systems such as wind turbines are gaining popularity due to net-metering laws. In its grid-connected mode of operation, a DG unit is connected to a utility power network by an agreement made with a distribution network operator (DNO). In general, a DG unit in its grid-connected mode is controlled to feed a certain amount of real power into the network. The amount of the power supplied at any point in time is dictated by the contractual agreement between the DG owner and a local power distribution company and this amount depends on the amount of connected local load and power market situation. Control systems for small grid connected wind turbine have an important role to maintain the grid connection for different conditions. During the past few years, several single phase inverters have been developed to operate small grid connected wind turbines. Such an inverter is important for the turbine to operate safely and also to supply clean power into the grid.

2.2 Control Systems

With development and utilization of wind energy recently, grid connected inverters are widely used as essential power electronic devices in wind power systems, especially in wind generation systems with variable speed constant frequency generators (turbines) [27][28]. With pulse-width modulation (PWM) control, the ac side of the grid connected inverter has the abilities of controllable power factor, sinusoidal output currents and bi-directional power transfer [29][30][31]. Power rating of grid connected inverter in wind power generation systems is usually high, therefore switching frequency of the inverter is usually limited, 1kHz to 3kHz . The relatively low switching frequency may cause the current harmonic to increase in the output current of the inverter. When an inverter is operating stand alone mode, the power quality is determined by the output voltage quality of the inverter [32]. However, when an inverter is connected with the power grid directly, point of common coupling (PCC) voltage is not controllable and the power quality is determined by the current quality only [33]. Therefore, grid connected inverter systems with stable operation, which reduce output grid current harmonics, are gaining more and more research interest. Typically, grid connected inverter systems like STATCOMs, active filters, and UPFCs, use series inductances to reduce switching frequency harmonics of output current. However in low switching high power grid connected inverter systems, large inductance is required to reduce switching frequency harmonics. This increases system cost and deteriorates control of the inverter. LCL filters are widely used in grid inverters to reduce the switching frequency harmonics while lowering the inductance requirements [34][35][36]. However, LCL filters increase system order and the direct closed loop current control in [37] and the control strategy proposed in [38] has some limitations due to system stability. Microcontroller based islanding detected grid connected inverter in [39] showed under/over voltage and under/over frequency islanding detection algorithm. The system based on a microcontroller from Microchip Technology Inc. PIC family. A PIC microcontroller searches the under/over voltage and under/over frequency from utility grid and process the value of voltage and frequency for turned on-off relay between grid connected inverter and utility grid

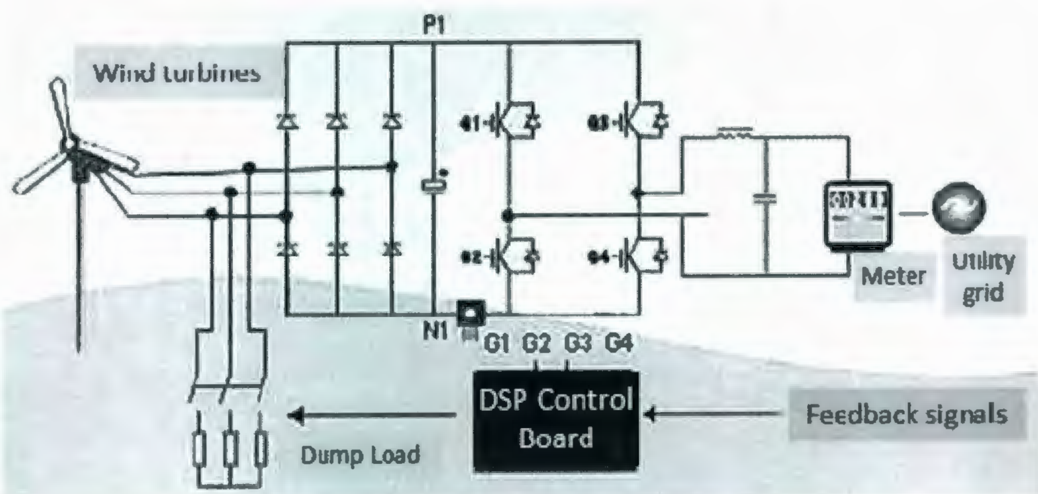

Fig. 2.1: Connection Diagram of Small Wind Turbine Grid Connected System.

Small wind turbine grid connected system designed by Sinostar Lighting Group Ltd. [40] includes small wind turbine dump load, grid-connected inverter, meter and power switchboard. When wind speed reaches the cut –in speed, the AC power from the wind turbine will be fed in the utility grid after rectifying and filtering stage. If the wind speed is too large, part of the dump load will be connected to the wind turbine to keep the constant power fed to the utility grid. Figure 2.1 shows the connection diagram of a typical Small Wind Turbine Grid Connected System.

GINLONG Technologies [41] is designing and manufacturing grid connected inverters for small wind turbine systems which is able to respond to very quick input voltage change and very fast output power response as well 40 point programmable, linearly extrapolated power curve.

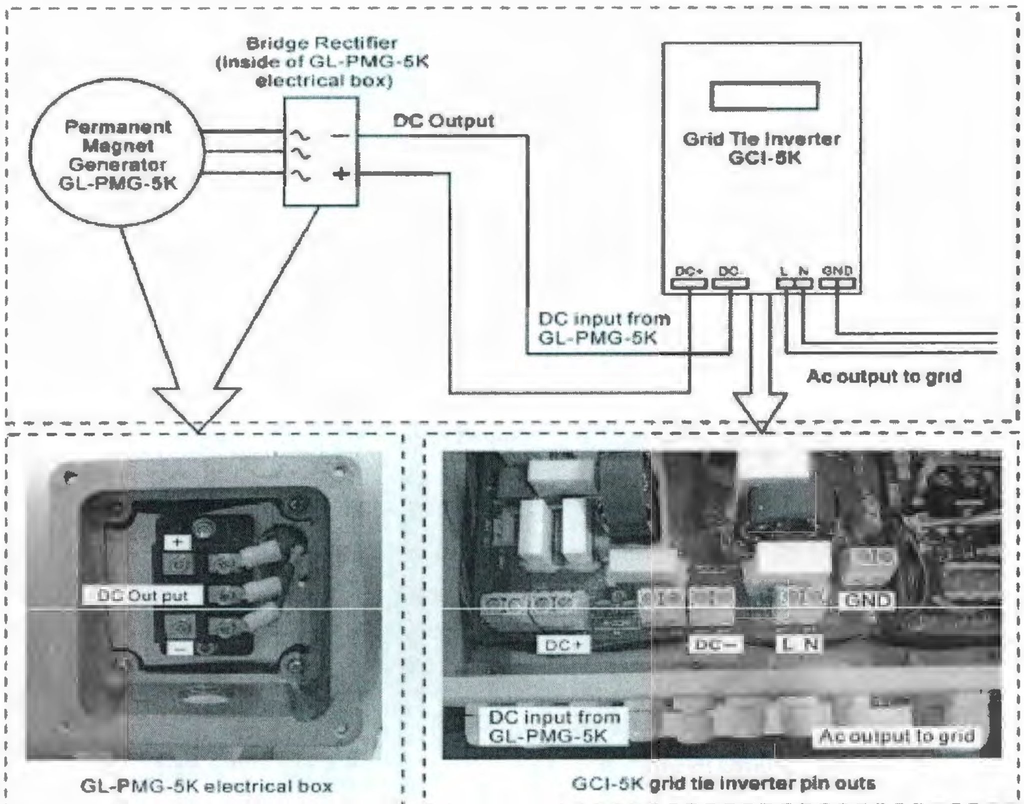

Fig 2.2: Wiring diagram of Grid Tie Inverter (GCI-5K)

Current controlled (PWM) inverter technology is used with wide input voltage range. Figure 2.2 shows the wiring diagram of GINLONG grid tie inverter.

Details of its control system are still unknown. Therefore, an extended research and investigations are still required to design a controller for small grid connected inverter.

S. Ali Khajehoddin *et al.* [42] shows two stage grid connected converter for PV systems. The first stage performs both Maximum Power Point Tracking (MPPT) and the decoupling tasks with a minimum number of components with optimized values. The second stage is a current source inverter employing a modified modulation technique that injects a current with low total harmonic distortion into the grid at unity power factor. The output power pulsation from the input power generation of MPPT can be resolved by a big electrolytic capacitor in the range of mF at the photovoltaic (PV) terminals, which in turn decreases the lifetime and increases the volume, weight and cost of the converter. An auxiliary circuit can resolve the problem which draw constant current from the input and generate a high direct current (DC) voltage at the middle stage to supply [43,44].

The above discussed inverters are not suitable for low power applications and exhibit low efficiency due to high voltage ratings. It also has extra switching circuits, hardware and control system configurations are complex which make the overall system expensive.

In this research a cost effective PC based control system is proposed for small grid connected inverter. 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. This chapter shows selection of single phase grid connected inverter, the system instrumentation in details for the measurements of the system parameters and installation of low cost measuring instrumentation for grid supply issues.

2.3 Selection of Single Phase Grid Connected Inverter

Many distributed generation systems are connected to the grid through inverters and these need to be controlled to maintain a stable grid. The most useful classification in wind turbine industry is based on speed. Wind turbine 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 [45] that increases the public interest on small induction generator based grid connected wind energy conversion system. "Net-metering" is a simplified method of metering the energy consumed and produced at a home or business that has its own renewable energy generator, such as a wind turbine. Under net metering, excess electricity produced by the wind turbine will spin the existing home or business electricity meter backwards, effectively banking the electricity until it is needed by the customer. This provides the customer with full retail value for all the electricity produced. [46]. 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 [47]. In a variable-speed wind turbine, the generator is controlled by power electronics equipment, which makes it possible to control the rotor speed [48]. However, controlling of variable-speed wind turbine is complex and increases the system cost compare to the higher production.

During the past, several controllers have been developed to operate small grid connected wind turbine. Such a controller is important for the turbine to operate safely and also to supply clean power into the grid. Controlling the associated grid tie inverter can control the output power feed by a distributed generation system to the grid. Grid connected inverter works in different modes such as stand-by mode, connecting mode, grid mode, and fault mode. In stand-by mode the inverter is ready to switch into Grid mode. If the power generated by the wind turbine is insufficient for grid operation, the inverter remains in stand-by mode until the wind turbine has generated sufficient power to switch into connecting mode. The inverter switches from stand-by mode to connecting mode after compiling the system predefined value. The wind turbine connects the inverter to the grid If the system values are acceptable. Minimum connecting times are specified by utilities and authorities and may differ from region to region. In Grid mode inverter is connected to the grid and delivers power to the grid. The inverter only leaves grid mode if a failure occurs or the wind power disappears. In this mode the inverter always works in the MPPT (maximum power point tracking) mode. This is the device's normal operating mode. The power taken by the inverter from the wind generator is always more than the power supplied by the network. The difference is the so-called power loss of the inverter. It determines the conversion efficiency of the device. The power loss is emitted as heat. When there is a fault happen, the inverter will switching off and go into fault mode to protect the wind power system.

The selected 250 watt single phase grid tie inverter UWT-I-250 manufactured by SWEA Europe and intended for home use only. Only wind turbine can be used which has a power out of 24-36-48 V AC or DC. So it can operate fixed and variable speed wind turbine. The inverter connects wind turbine to the grid without using batteries. It is programmed for a desired input voltage versus output power characteristics and is a cost effective solution. Figure 2.3 shows the system configuration of a grid-connected generation system.

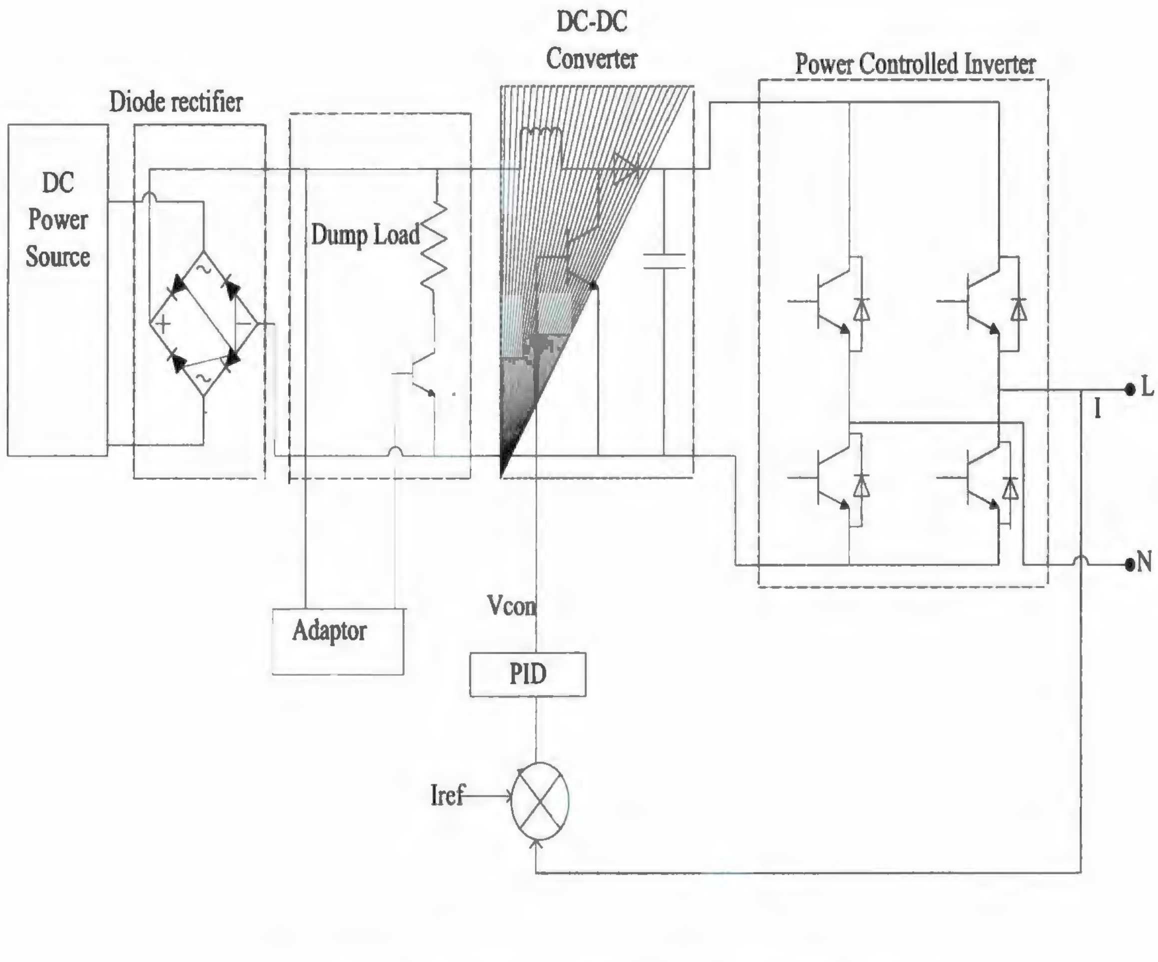

Fig 2.3: Grid Connected Inverter Topology and Control

The output power of wind turbine generation system is connected to the grid through a DC-DC power converter and a single phase grid tie DC-AC power inverter. The diode rectifier converters the AC to DC output of 3 phase wind turbine. If the output power is more than 250 watt (up to 1000 watt) then 4pcs of inverters need to be installed in parallel to the grid through the adaptor. Adaptor box or AP-box is in between the wind turbine or diode rectifier and grid tie inverter. The adaptor power is simulating the battery power to start up the DC out of a wind turbine. DC input voltage of the inverter should never be exceed 52 V. AP-box also works as a safety box when the wind speed becomes too high. It will switch on the dump load automatically when the DC out of the wind turbine becomes higher than 52 V and slows down the speed of the wind turbine. The dump load is connected via the adaptor to the wind turbine to break the wind generator and to avoid damage of the inverters. The dump load is automatically turned on when DC input of the inverter is higher than 52V. The DC input of the inverter is adjusted at 54 V DC. In this way the AP-box will be switched earlier than the inverter and gives protection to the connected inverter or inverters. During this period the inverters are functioning normally till the dump load is shut down the wind turbine below 17 V DC. At 17 V DC the speed of the wind turbine is low enough to switch off the dump load.

There are two color of CPU are installed into the inverter. They are Green CPU and Red CPU. The Green CPU has installed for the wind turbine which maximum power output 48 volts like Air-X-48 V DC output wind turbine. The Red CPU is used for 24 volts or 36 volts DC output wind turbine such as Air-X-24 V DC. As the inverter is programmed for input voltage versus output power characterized, so the installed power curve can be changed and adjusted according to the selected wind turbine. The communication is done via a hyper terminal through serial cable connected to the inverter. This requires some calculations to change the steepness of the curve. The steepness is expressed as a number of voltages per ampere. Figure 2.4 shows power curve for Green and Red color CPU. Green curve shows for the wind turbine which is started at 27 volts and supplied power to the grid is 200 watts 49 volts as well as Red curve shows with starting voltage 27 volts and supplied power to the grid is 200 watts 49 volts.

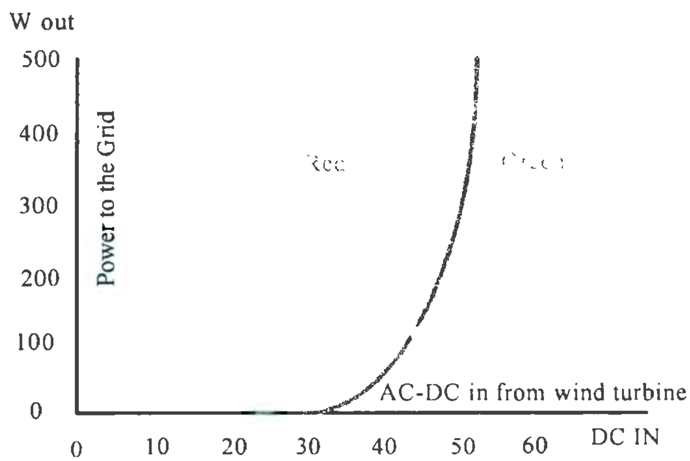

Fig.2.4: Power curve for Green and Red color CPU

The inverter was programmed for a desired input DC voltage versus output power. The installed power curve steepness into the CPU was changed and adjusted by using serial cable RS232.

Power Curve Steepness Adjustment:

Start-up voltage (B) = 24 V DC (representing a DG system)

Power fed to the grid at 51V output is 180 W

Difference between start till end voltage= (51-24) =27 V

Current at 180 W at 51 V DC=3.5 A

The steepness of the curve (A) =27 V/3.5 A=7.7 V/A

Figure 2.5 shows power curve steepness adjustment into the CPU.

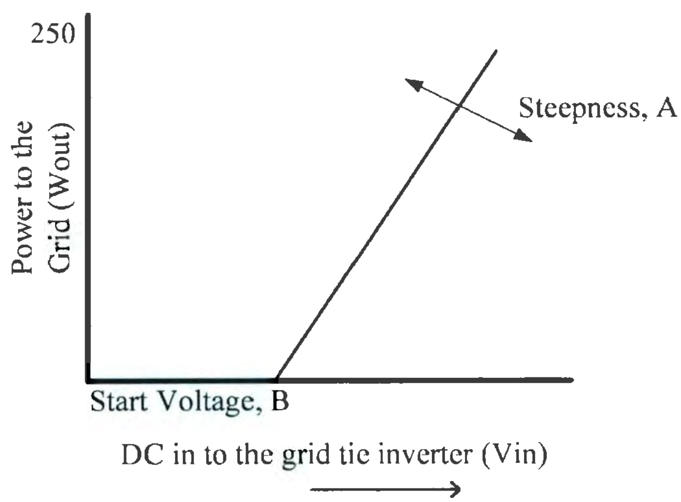

Fig. 2.5: Power Curve Steepness Adjustment into the CPU

2.4 System Instrumentation

A low cost instrumentation is designed for measuring the parameters of the small grid connected inverter. Figure 2.6 shows the instrumentation for single phase grid connected inverter of the developed remote control distributed generation system.

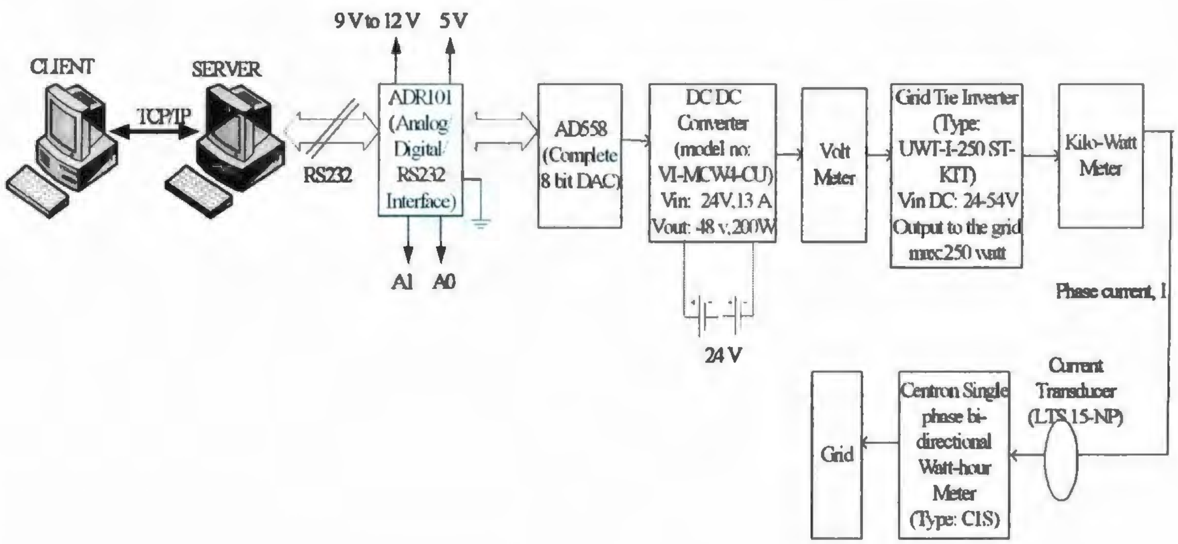

Fig 2.6 Block Diagram of the System Instrumentation

The measurement system consists of current transducer, power measuring unit, DC-DC converter, digital to analog converter (AD558), data acquisition card (ADR101) and all instruments directly or indirectly connected to PC. The DC-DC converter is powered by

24 V power supply. The output of the converter boosts up the input voltage to 48 V DC and passes through the grid tie inverter. The output voltage of ADR101 is sent to PC through digital to analogue converter. Analogue output voltage controls the trimmed voltage and rated voltage of the DC-DC converter. According to the inverter characteristics the output power to the grid is changed depending on the wind turbine. Single phase watt-hour meter measures the power fed to the grid.

2.4.1 Voltage Measurement

Figure 2.6 also shows the measuring block of the DC terminal and grid side voltage in RMS value. Voltmeter, watt-hour, current transducer and single phase bi-directional watt hour meter are used to measure the DC and grid side voltage and power. Voltmeter is used to measure the output voltage the DC-DC converter of DC terminal.

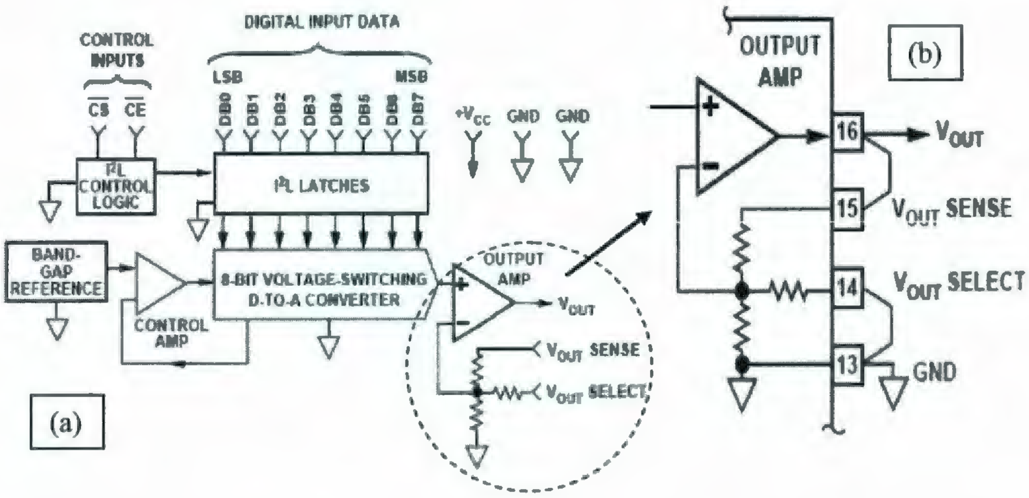

Fig 2.7: (a) DAC Block Diagram and (b) 0-10 V Output Range Connection Diagram

Closed loop multi range (0 to ± 15 amps) current transducer (LTS 15-NP) is used which detects the output primary current of the grid tie inverter and converts it to analog output voltage V_{out}. Analog output voltage can be calculated by using the following equation:

$$V_{out} = 2.5 \pm (0.615 X I_P/I_{PN}) \ldots\ldots\ldots (2.1)$$

Where,

V_{out}=output voltage

I_P=primary current measuring range, and

I_{PN}=primary nominal RMS current.

The output of the data acquisition card ADR101 is passed through DAC 558 to provide analogue output. AD558 consists of four major functional blocks, fabricated on a single monolithic chip. Figure 2.7 shows the functional block diagram and connection diagram of the DAC.

The main D-to-A converter section uses eight equally-weighted laser-trimmed current sources switched into a silicon-chromium thin-film R/2R resistor ladder network to give a direct but unbuffered 0 mV to 400 mV output range. The transistors that form the DAC switches are PNPs; this allows direct positive-voltage logic interface and a zero-based output range. The high speed output buffer amplifier is operated in the non inverting mode with gain determined by the user-connections at the output range select pin. The gain-setting application resistors are thin-film laser-trimmed to match and track the DAC resistors and to assure precise initial calibration of the two output ranges, 0 V to 2.56 V and 0 V to 10 V. The resolution is 8 bits (2^8). All reference, output amplifier and logic connections are made internally. As the controlled voltage, V_{con} range is 0 to 5 volts, the 0 to 10 volts output range has been chosen with required power supply of +11.4 V to +16.5 V. Voltage divider circuitry is used to divide the output voltage of DAC. The photograph of the remote control DG instrumentation is shown in Figure 2.8.

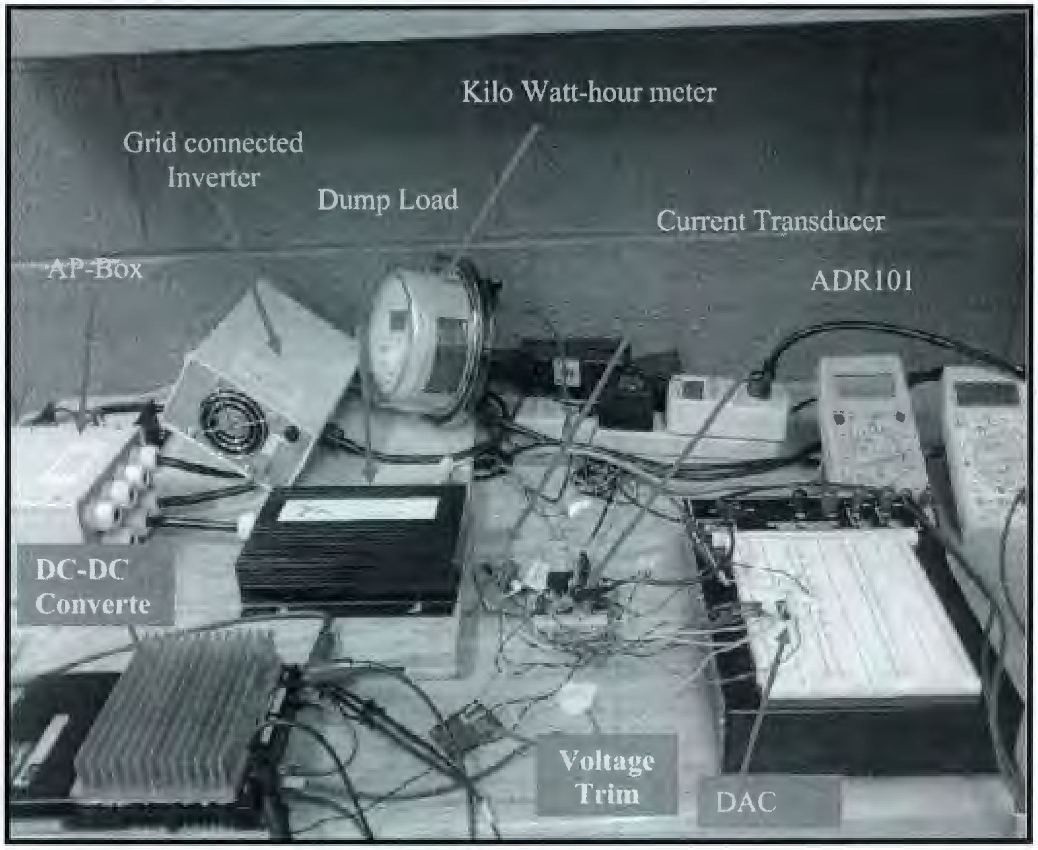

Fig 2.8: Photograph of the Remote Control of DG Instrumentation

2.4.2 Power Measurement

The measured power identify the grid connected inverter is operating or monitoring in grid mode from dispatch center. To obtain the power measurement watt-hour meter and single phase bi-directional watt hour meter are used. The Watt-hour power meter is a very useful device that allows checking the used power. The meter has a large LCD display that is used to show consumption by the Kilowatt-hour (kWh). Meter also allows monitoring the quality of the electricity by displaying voltage, line Frequency and power factor. Single phase bi-directional watt hour meter is used to the grid side. The meter measures active energy in single-phase two wire or three wire alternating current power grids. Bidirectional active energy measurement is indicated by LED forward and backward direction.

2.5 Summary

The selected single phase inverter, system instrumentation, operation and installation are described in this chapter. The block diagram of the system parameters and measuring circuits are presented in details. Finally, typical installation requirements for a grid connected system are described in terms of voltage and power.

Chapter 3: Selection of System Control, Design and Implementation

3.1 Introduction

This chapter presents the design of a new, simple and economical controller to control power supplied to the grid from an inverter based on a control command from a dispatch centre. The designed control system had been developed using a DC-DC converter and data acquisition card ADR101 which was programmed using Quick basic. The chapter also focused on implementation of the design controller under grid connected mode and system simulation.

After the introduction of net-metering laws, a consumer can install a small wind 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 to provide reliability, quality and power at the grid and also to provide safe operation of the wind power generation system. The operational requirement of grid connected inverter based wind turbine includes the automated power supplied to the grid. This situation may occur due to the level of wind power available and also due to the grid availability. In order to meet the operational requirements, it is necessary to control and monitor the system behavior in such a way, that controller has the capacity to control power supply to the grid under any stipulated condition. The system controller operates by measuring the system parameters (such as DC/AC output voltage of a wind turbine), converter output voltage, and the current and power flow between generation and the grid sides. Therefore, it is challenging design the proper instrumentation, to measure the control variable of a generation system; ensuring accuracy with low cost budget.

These issues can be overcome by the designed controller as the system could be monitored from remote/near control place. This chapter describes the implementation of the proposed control system. To investigate the feasibility of the proposed topology and control algorithm, inverters simulation was incorporated in this study which is discussed in the following sections.

3.2 Selection of System Control

In order to obtain the proposed implementations there are several types of control system available. For example, PC based control, DSP based controller and micro-controller. A cost effective solution to inverter design is found in [49] *et.al* Liviu Mihalache, and Mihai Chis based on digital signal processor (DSP). A 15kVA IGBT-based DSP-controlled inverter method was built and the control was implemented with an ADMC401 DSP. Figure 3.1 shows the inverter control technique used in this approach. The control system was implemented without using a current loop. So, the main output filter introduced very high impedance around its resonant frequency. The immediate effect was any harmonic current due to a nonlinear load around the filter resonant frequency were filtered out. The resonant frequency had determined a significant voltage harmonic component in the output voltage spectrum. The main filter resonant frequency could significantly reduce the unwanted influence of output filter impedance, when it moved further from the lower main harmonics of the inverter (3rd, 5th, 7th, 9th, etc).

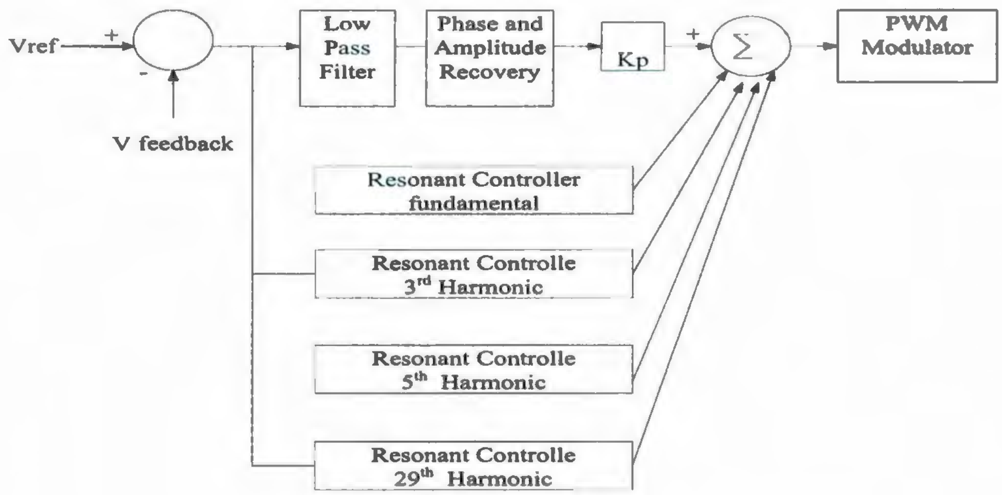

Fig. 3.1: ADMC 401 DSP-based Harmonic Control

(Liviu Mihalache, and Mihai Chis *et.al, 2003*)

Single phase sinusoidal pulse width modulated microcontroller based inverter was designed by B. Ismail [50]. The controller was able to generate SPWM pulses and necessary waveform to control the inverter frequency through the designed switching pulses. This inverter was designed either for stand–alone or for grid connected mode for direct supply of photovoltaic power. Figure 3.2 shows the designed switching strategy for single phase inverter.

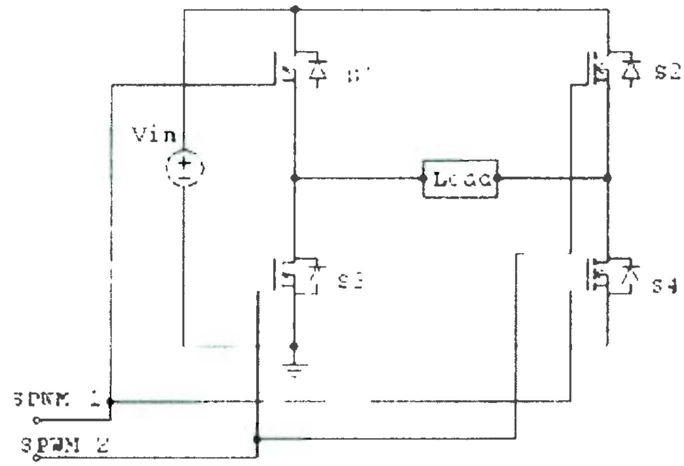

Fig.3.2: Full Bridge (4-pulse) Single Phase Inverter Topology

Microcontroller controlled switch S1 and S4 by generating SPWM 1. Switch S2 and S3 also operated through designed microcontroller by generating SPWM 2. Both SPWM 1 and SPWM 2 used the same control signal generated by the microcontroller. The difference is SPWM 1 signal was leading SPWM 2 by half cycle or 180 degree of the switching signal

The discussed DSP and micro-controller systems are expensive and not suitable for low cost DG system. The proposed PC based controller requires very low computing power. A data acquisition card with RS232 serial cable is the cheapest and QuickBasic the most convenient program as compared to other available options. Therefore, a low cost data acquisition card ADR101 has been selected to design the proposed controller. ADR 101 is a low cost serial data acquisition and control interface device. This device has two 8-bit analog inputs (0-5VDC) and 8 digital I/O lines individually programmed as output or input. It requires low power (5 volts 15mA). ADR101 can be easily used with Quick Basic and TURBO C programs [51]. The digital input/output voltage of ADR is adjusted by a Quick Basic control algorithm. Interface to PC through three wire RS232 serial cable. In this research AN0 is used as an analogue input and PA0 to PA7 are used as a digital output. The D/A converter AD558 conversion of the digital output signal results in a corresponding 8 bit analogue signal. The TCP/IP link is used to access an ADR card on a remote computer. In this research Quick Basic is used for programming the controller. The desired method for the system controller is PC based and the input power fed by the inverter to the grid is controlled by the control voltage using ADR101. Inverter output current is measured by a current transducer. The output of the current transducer is sent to the analog input of the data acquisition card ADR101. Subsequently, the result of the ADR is a digital signal which is sent to the digital to analog converter (DAC). The analog output of DAC is connected to control voltage of DC-DC converter to be sent to the grid in order to adjust the grid power. Output reference current signal comes from the Internet or existing data files in PC and indicates the total power.

3.3 Controller Design for Grid Connected Inverter

The number of wind power units installed in power systems around the world has grown significantly in the last two decades. The trend today is to construct large wind power farms offshore. Many of the installed plants are, however, small farms or individual plants on land connected to the distribution systems. In Europe a few countries, with economic and politic prerequisites, distinguish themselves from the rest; Spain, Holland, Germany and Denmark. In western Denmark the capacity of installed wind power has developed as presented in Figure 3.3. The maximum load in the same area is approximately 3600 MW. The present figure of 2400 MW shall be compared with peak load of 3600 MW in the same area, (Eltra 2000).

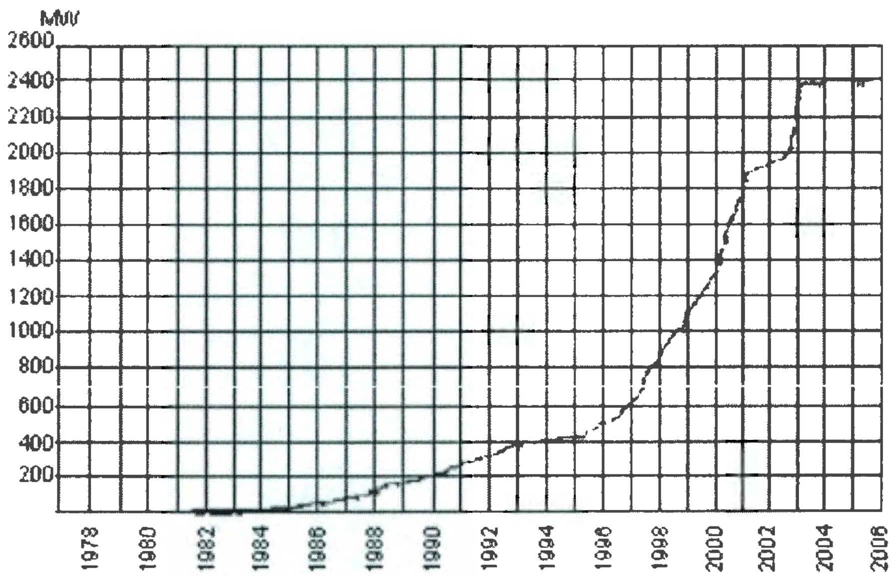

Figure 3.3 Wind Power Developments in the Eltra Service Area

Source: www.eltra.dk

In a distributed power generations system such as wind turbine, the output power is controlled and conditioned by a high power converter. Power electronic converters (PEC) can control both active and reactive power. The short-circuit current magnitude from a PEC is not considerably larger than the rated current; a typically value mentioned is 115%. This is due to the low ability of semiconductors to withstand over currents.

For that reason, the electric characteristic of the DC-DC converter should match that of the wind turbine. As a result, the DC-DC converter can be used to adjust power output of a distribution generation system.

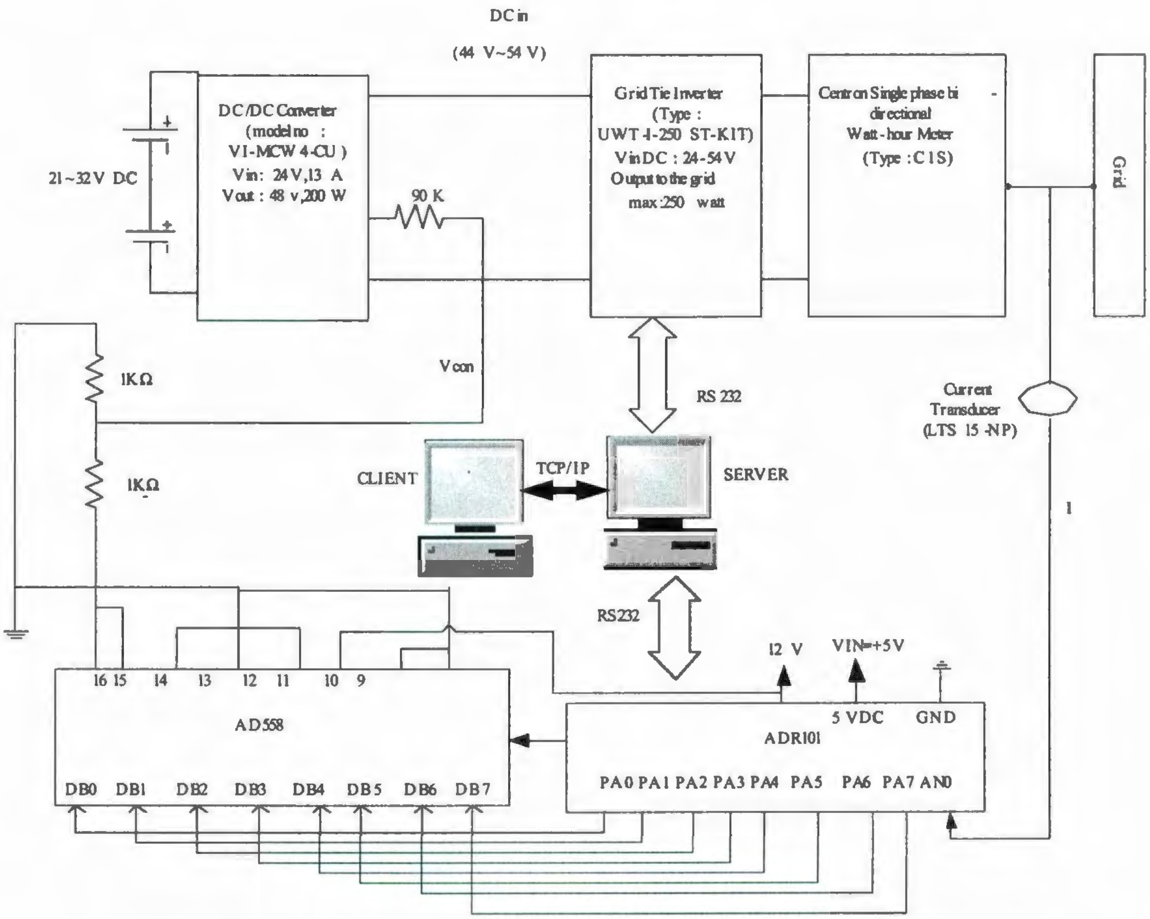

Fig. 3.4: Circuit Diagram of the Proposed System

Therefore, a DC-DC converter configuration and control strategy should be different from those of the conventional converter. In order to meet the system operation requirements, a system needs to be interfaced through a set of power electronic devices.

The interface is very important as it affects the operation of the DG system as well as the power grid. In addition to that, different controllers for the interfacing power electronics circuits in DG also need to be designed for the overall system to improve its performance and to meet certain operational requirements. Those requirements are output voltage control, active power output control, reactive power output control, peak-load shaving control, etc. The circuit diagram as shown in Figure 3.4 represents the designed remote control system of grid connected. It consists of a DC-DC converter, a ADR101, a PC and the system parameter measuring instruments.

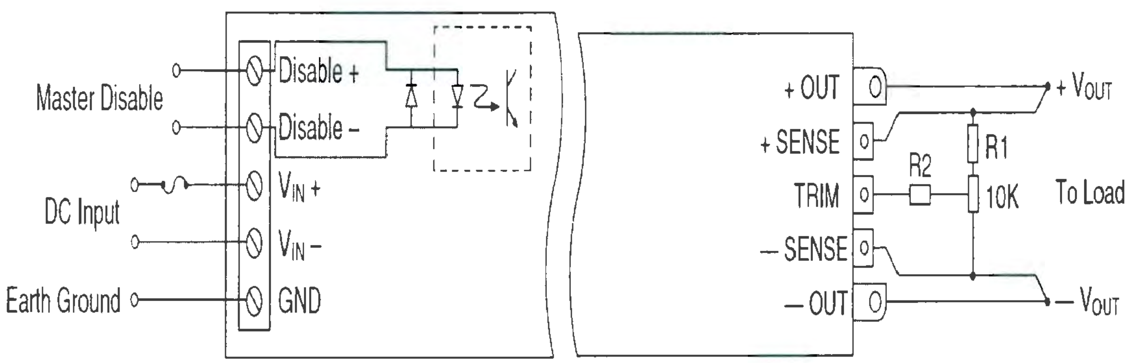

Fig 3.5: Block Diagram of the DC-DC Converter

The power converter shows in Figure 3.5 supplies power from DC power supply and provides a optimal power solution to meet the voltage, noise, and transient protection input requirements of commercial, industrial, military, and telecommunications applications [52]. Its normal operating input voltage range is 21V to 32V, 13 amps. The Master Disable input is optically isolated and incorporates a reverse polarity protection diode. It also has a single output and voltage trimming arrangement. The converter rated output voltage is 48V and the voltage trimming rage is ±10% of the rated output voltage (44V to 54V).

Input DC voltage of the inverter is adjusted by controlling the DC-DC converter. A PC which is connected with the ADR101, receives the required output reference power signal from a dispatch center via the Internet. The TCP/IP link is used to access an ADR card on a remote computer. The PC measures the power being fed by the inverter to the grid and uses a ADR101 to control the DC-DC converter to adjust the power flow to the grid. The output voltage of DC-DC converter is controlled by the ADR101 as well as input DC voltage of the inverter. ADR101 control the trimming voltage of the converter which is known as control voltage, V_{con} from 0 to 5 volts. The control logic was programmed by using the Quick Basic. The information about the voltage and power were acquired by the measuring circuitry which was explained in Chapter 2. The inverter was programmed for a desired input DC voltage versus output power before it was connected with the grid. Figure 3.6 shows the photograph of ADR101.

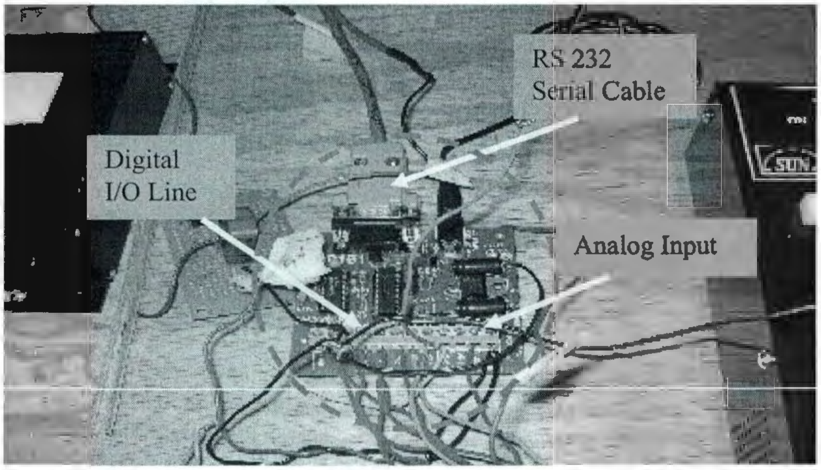

Fig. 3.6: ADR101.

3.4 Implementation of the System Controller

The proposed control algorithm for grid connected inverter was implemented in the laboratory using ADR101, which was controlled by PC via the internet. Reference current signal, I_{ref} was stored into the existing file on a PC or can come from a dispatch center.

The control algorithm in which power control decision is taken based on input phase current and digital output of ADR101. To get the output from the controller the ADR need to be configured first. The data input for the ADR can be fed from any reference sources. After that the port A of the ADR was configured as output port and with the input data it can be initiated. The ADR then can read the current input as analog signals. The measured current then compared with the reference set current of the input data. If the measured current is higher than the reference current then the digitalized output of the voltage will be decrease, if not then there will be increase in the output. There will be a time delay for the data transfer. The program will continue to generate the outputs until the end of data. The flow chart of the implemented control algorithm is shown in Figure 3.7.

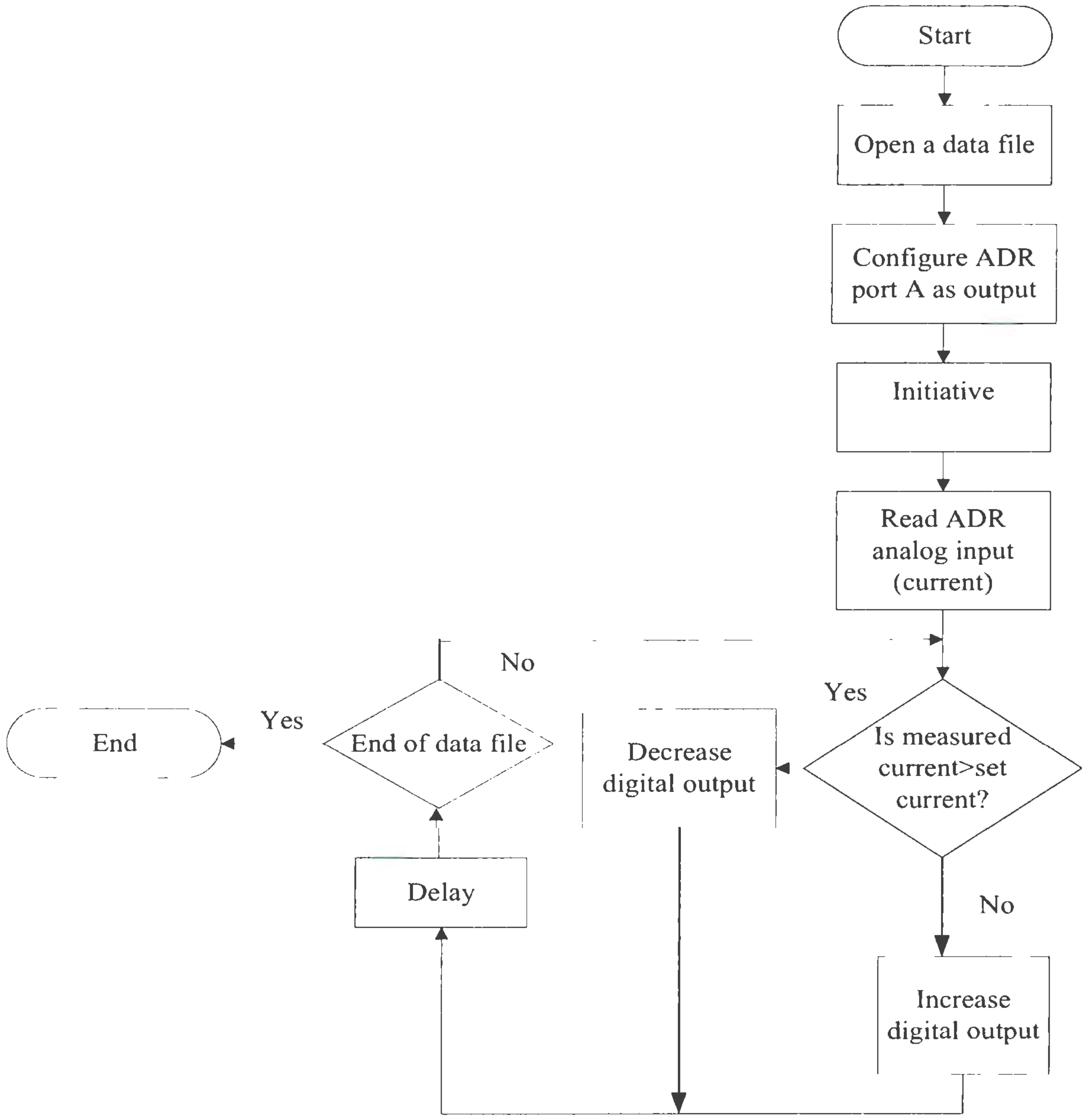

Fig 3.7: Flow Chart of the Control Algorithm

3.4.1 Simulation of the Control System

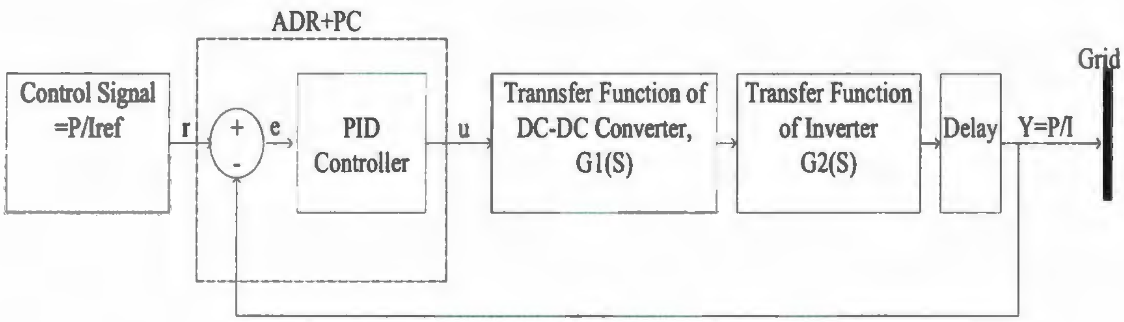

Fig. 3.8: Close Loop Diagram of the Proposed Control System

To investigate the feasibility of the proposed topology and control algorithm for grid connected inverter, simulation was done. In this research SIMULINK was used for system simulation. SIMULINK is a part of MATLAB that can be used to simulate dynamic system. It has a high flexibility and expandability which allows a detailed analysis of an electrical system. Another advantage for the use of SIMULINK is an automatic source code generation with the Real-Time Workshop. Figure 3.8 shows close loop diagram of the proposed control system. The reference signal is the set point of desired current label.

Error, *e* is defined as the difference between set-point and output, *Y*.

$$e\ (error) = (set\text{-}point) - Y\ (output) \qquad (3.1)$$

The variable being adjusted is called the manipulated variable which usually is equal to the output of the controller. The output, U of a proportional integral derivative controller (PID) will change in response to a change in measurement or set-point. The characteristics of the parameters, the proportional (P), the integral (I), and the derivative (D) controls are used to obtain a desired response. In Figure 3.9 DC-DC converter and grid connected inverter were considered as a plant. The controller provided the excitation for the plant and designed to control the overall system behavior. The transfer function of the PID controller looks like the following:

$$K_P + K_I/S + K_D = (K_D S^2 + K_P S + K_I)/S \ldots\ldots\ldots\ldots\ldots (3.2)$$

Where,

K_P = Proportional gain,

K_I = Integral gain, and

K_D = Derivative gain

By tuning the three constants P, I and D in the PID controller algorithm, the controller provided control action designed for the proposed system. A PID controller also called a PI, PD, P or I controller in the absence of the respective control actions. The controller tuning was done by SIMULINK. In chapter 4 simulation results were discussed.

Figure 3.9 shows the step response of DC-DC converter in channel 1 and current transducer in channel 2. Analyzing the output response, the first order transfer function of the DC-DC converter and grid connected inverter can be expressed as, *DC-DC converter transfer function* $G_1(S) = G_{DC}/(\tau_1 * S+1)$....... .(3.3)

Here,

G_{DC} = DC gain for *DC-DC converter*

τ_1 = *Time constant* = 50 m.sec, which was determined from channel 1 in figure 3.7.

= 0.05 sec

G_{DC} = Output voltage/input voltage... (3.4)

== 2/50=1/25=0.04

Hence, $G_1(S) = 0.04/(0.05s + 1)$

Grid connected inverter transfer function $G_2(S) = G_{AC}/(\tau_2 * S+1)$.......(3.5)

Here,

G_{AC} = gain for Grid connected inverter

τ_2= time constant =180 ms, which was determined from channel 2 in figure 3.7.

=0.18 sec

$G_2(S)$ =Output voltage/input voltage

= 0.2/2=0.1

Hence, $G_2(S)$ = 0.1/(0.18s + 1)

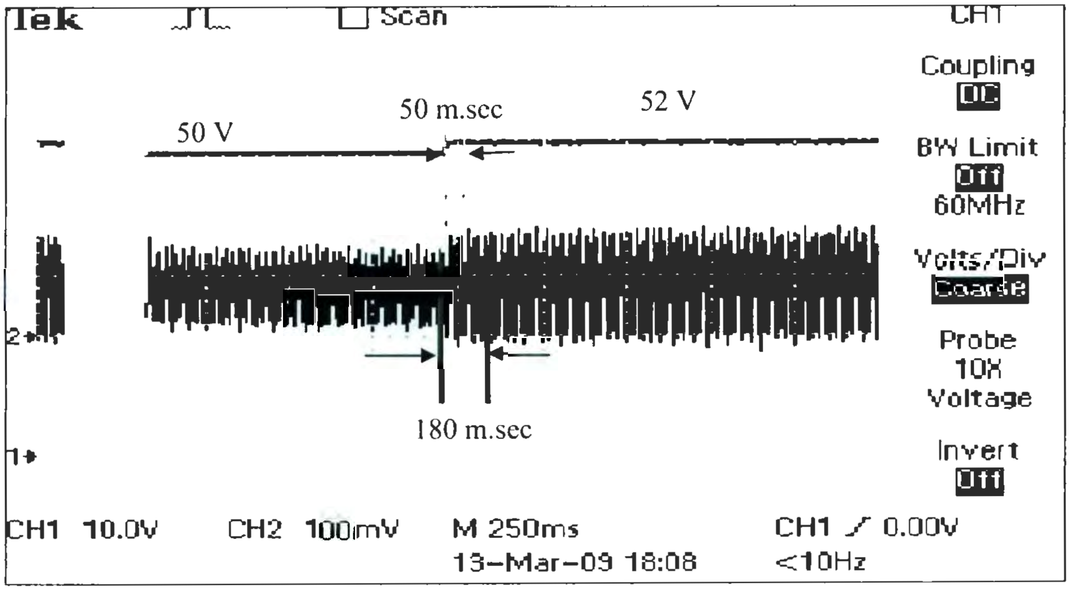

Fig. 3.9: The Experimental Step Response of DC-DC Converter and Current Transducer

Figure 3.10 shows Matlab Simulink block diagram of the proposed model used to perform the simulations. The reference control signals R(S) are shown by unit step block. This block contains reference current signal coming from dispatch center or existing data file into the PC. Two types of current and power steps can be applied using this simulation scheme. In a proportional controller represents the controller as a gain, Kp. The control action is proportional to the error and provides a decrease in system rise time. This signal U(s) sent to the plant and the new output Y(s) will be obtained. DC-DC converter and grid connected inverter transfer functions are shown in dotted line referred as a plant.

This new output Y(S) will be sent back to the sensor again to find the new error signal E(S).The controller takes this new error signal and computes its proportional again. This process goes on and on. Scope shows the reference control signal and overall system output.

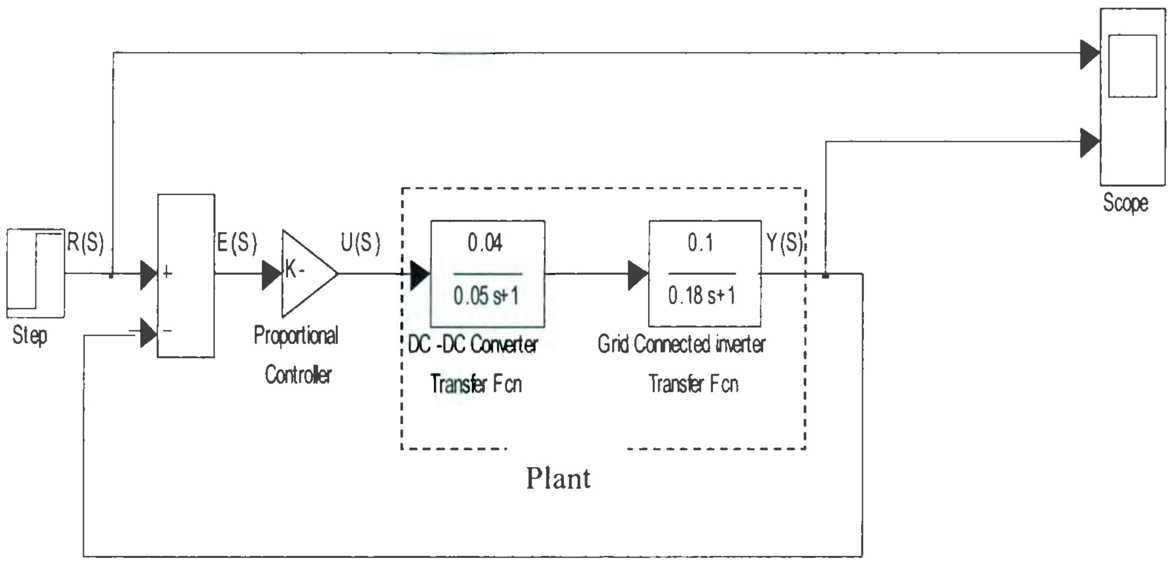

Fig. 3.10: Matlab Simulink Block Diagram of the Proposed Control System

3.5 Test Setup

In Figure 3.11 shows the test setup photograph for the designed remote control system. The remote power control system was PC based and the input power fed by the inverter (c) to the grid was controlled by the control voltage (V_{con}) using ADR101 (e). Inverter output, grid current (I_{grid}) was measured by a current transducer (f). The output of the current transducer was sent to the analog input of the data acquisition card ADR101.

Subsequently, the result of the ADR was a digital signal which was sent to PC through the DAC (h). The analog output of DAC was connected to the voltage divider (g). The output of the voltage divider was applied to V_{con} of DC-DC converter (d). By using V_{con} DC-DC converter controlled the inverter input voltage in order to adjust the grid power. The DC-DC converter was powered by 24 V power supply instead of wind turbine. The output of the converter boosted up the input voltage to 48 V DC and passed through the grid tie inverter. According to the inverter characteristics the output power to the grid was changed depending on the distributed generation system (DG). The system was connected through the AP-box (b) and the dump load (d). Single phase watt-hour meter (j) measured the energy fed to the grid. Watt-meter (k) showed the grid current, phase voltage and power supplied to the grid. Current probe (i) was used to monitor the grid current into the oscilloscope. Output reference current signal, I_{ref}, comes from the Internet or existing data files in PC and indicates the total power.

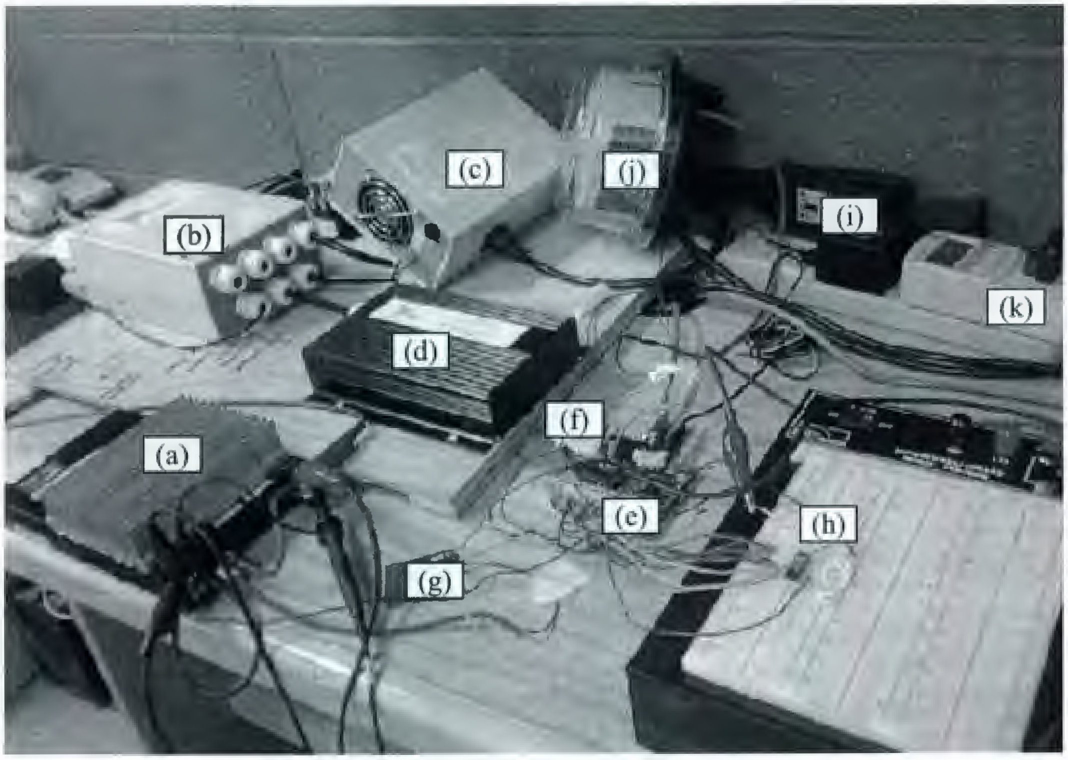

Fig. 3.11: Laboratory Setup for the Designed Control System.

3.6 Summary

Design and implementation issues of a low cost system controller for a small grid connected inverter were presented in this chapter. The operation of the system controller was based on PC. A PC receives the required output power signal from a dispatch center via the Internet. The PC measures the power being fed by the inverter to the grid and uses an ADR101 to control the DC-DC converter to adjust the power flow to the grid. The complete instrumentations to operate the system and flow chart of the control algorithm were also explained and the remote control operation of small grid connected inverter was described in this chapter.

Chapter 4: Performance Test Results

4.1 Introduction

This chapter describes several test results and discussion of remote control of grid connected inverter based distributed generator. The control system was tested to supply power to the grid using a command from an imaginary dispatch centre. The laboratory test result was also verified by simulation. The simulation result based on a Proportional (P) controller is also presented in this chapter.

The operation of the control system described in Chapter 3 has been implemented and tested in laboratory environment using PC and data acquisition card ADR101. It was discussed in Chapter 3 that, the control system supplied power to the grid based on control signal from dispatch centre. The proposed control system worked as expected which also indicated the performance of the developed low cost instrumentation. Moreover, an investigation was also necessary to test the closed loop control system. The investigated result shows the performance of the proposed remote control strategy and proves the effectiveness of small grid connected inverter performance. The entire experimentation was done using a 250 watt grid connected inverter system coupled with DC-DC converter, Lead Acid Battery, PC and ADR101. The discussion of the test results achieved from the proposed remote control technique based on simulation result is also included.

4.2 Simulation Results

After building the proposed model in Simulink, simulation results showed its dynamic behavior and expected results. Controller tuning method and simulation output are discussed in the following sub-section.

4.2.1 Tuning Method of the Controller

Controller tuning is the way of selecting the controller parameters to meet given performance specification. A well known Zieglar-Nicol'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 [53]:

- Start controller with a low gain
- Gradually increase the gain, until the saturation start
- Adjust the gain to make the saturation continue with a constant amplitude

- Record the proportional gain (K_p) and time constant (τ).

The above described tuning method is done by Matlab Simulink and the gain and time constant (τ) are from experimental result. The proportional gain (K_p) is obtained from tuning the controller. K_p adjusted the proportional response by multiplying the error. Table 4.1 and the calculated value are used to obtain Proportional (P) controller value.

Table 4.1: Simulation Parameters

P Controller	Gain		Time constant	
K_p=1700	G_{DC}=0.04	G_{AC}=0.1	τ_1=0.05 sec	τ_2=0.18 sec

The control system consists of PC combined with a ADR101. The Simulink model for the proposed remote control system driven by the grid connected inverter and DC-DC converter derived in chapter 3 is used as a plant. PC received the reference current signal from dispatch centre and the simulations were performed to track a reference current. The simulation for the plant with a P controller to track a reference current of 0.68 amps is shown in Figure 4.1. The proportional gain used in the simulation is K_P = 1700. This is the best K_P obtained when tuned for the grid current to go to a steady state without much over shoot. The simulation results in Figure 4.2 has initial overshoot because there is always a tradeoff between overshoot and the current tracking the reference current signal.

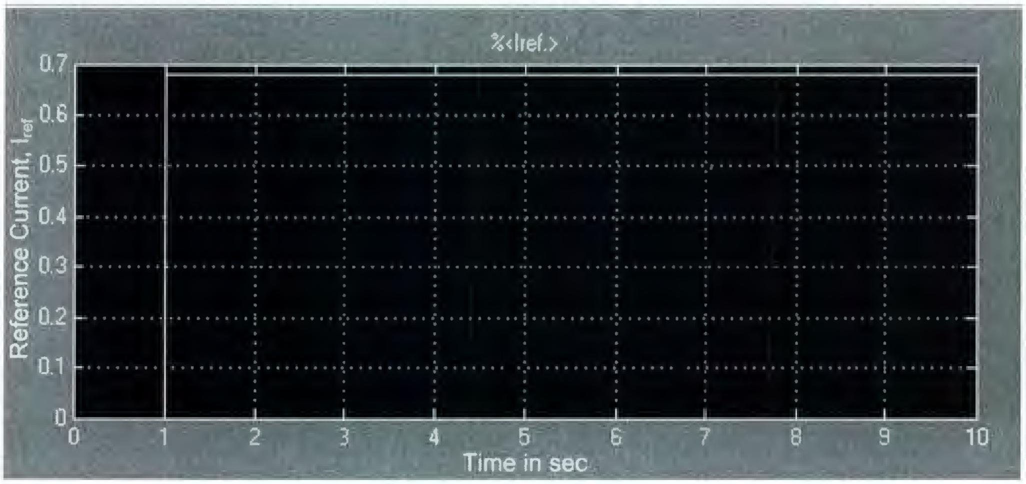

Fig.4.1: Reference Current at 0.68 amps

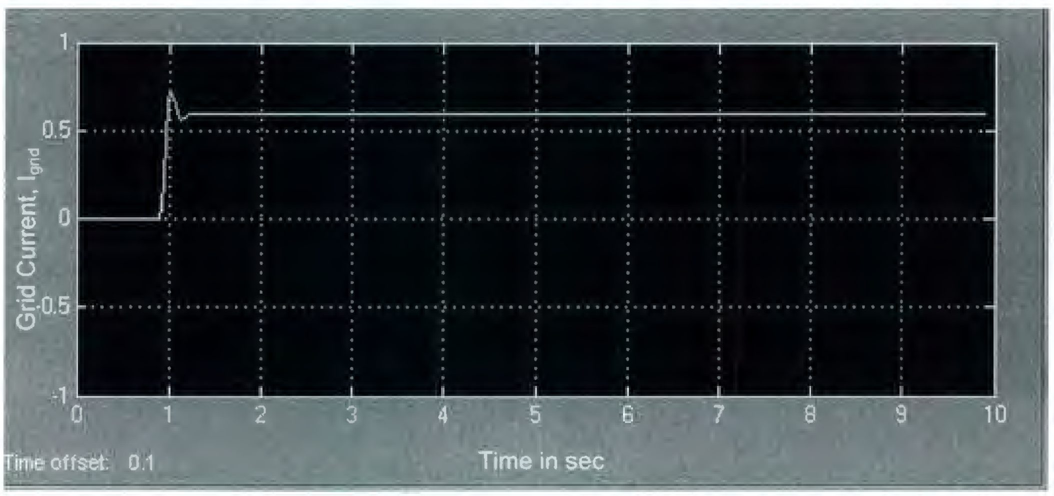

Fig.4.2: Output Grid Current of the Proposed System

Figure 4.3 and 4.4 showed reference step response at t=1s and output current of the grid connected inverter. The output current varied with reference current 0.32 amps.

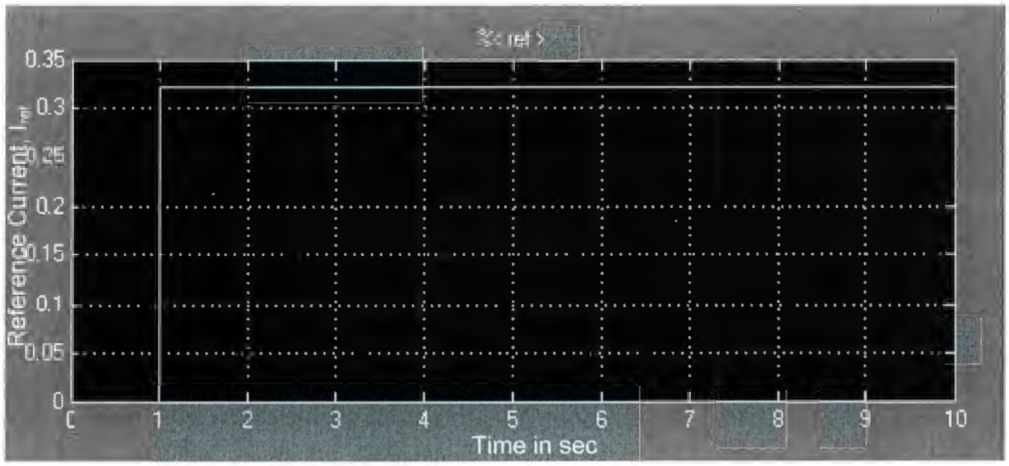

Fig.4.3: Step Response of I_{ref} at 0.32 amps

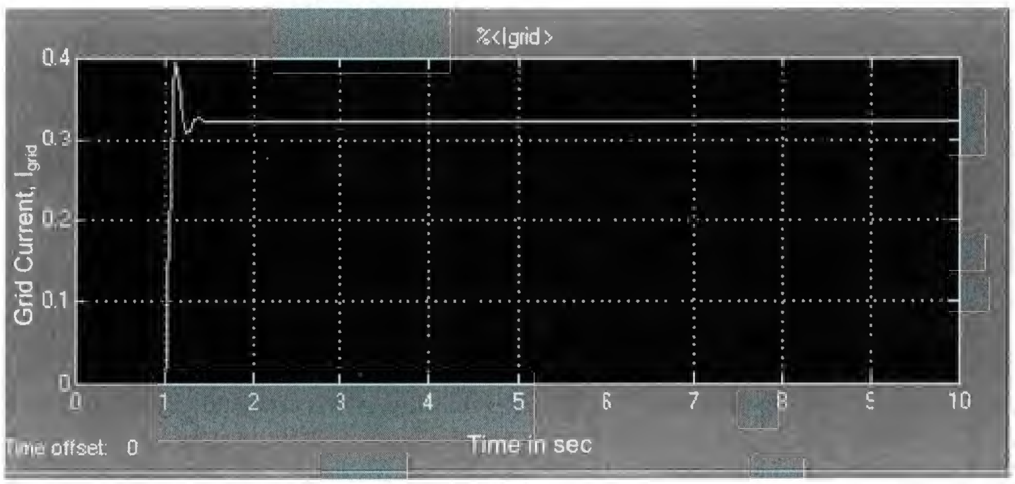

Fig.4.4: Output Grid Current Supplied to the Grid

4.3 Control System Test Results

The control system was tested while ADR101 adjusted the power supplied to the grid based on the output current of an existing data file into the PC. The user sets the reference current on the data file. Depending on the reference current the controller (ADR101) generates the output by varying the control voltage in the control loop. The test results of the proposed control system are discussed in the following sub-section.

4.3.1 Voltage Feedback Controller

The proposed remote power control system is PC based and the input power fed by the inverter to the grid is controlled by the output voltage of DC-DC converter using ADR101. The control voltage was calculated according to equation (4.1).

$$V_{con} = V_{in}\, x\ Decimal\ output/255 \qquad (4.1)$$

Where

$Vcon$ = control voltage,

Vin=input voltage,

Decimal Output = outputs from the ADR101 data acquisition card, 255 is a constant value for the card. Control algorithm was implemented in Quick Basic.

Table 4.2 summarizes the experimental results of the control system based on voltage feedback. After getting the power signal from reference data file via internet; controller controlled the power to the grid using ADR101. The Internet Protocol Suite, commonly known as TCP/IP. TCP/IP is the set of communications protocols used for the Internet and other similar networks. This link was used to access the ADR card on a remote computer. The client program (ADRSockclient is the client that runs on the remote computer) accepts a command parameter, transmits it across the network to the server program (ADRSocSrv is the server that runs on the computer hooked up to the ADR card) which issues it to the ADR card. Table 4.2 shows that controller control the converter output voltage at 47.6 volts by controlling the control voltage at 1.961 volts. The converter output voltage also changed the inverter output current which was 0.23 amps. With the increase of control voltage to 3.922 V, the converter output voltages increase to 51.4V and inverter output current was 0.57 amps. Similarly for 4.902 V control voltage DC-DC output is 53.3 V and inverter output current was 0.78 amps.

Table: 4.2: Experimental Test Results

Ref. Current (I_{ref})	Control Voltage (V_{con})	Grid Current (I_{Grid})	DC-DC Converter Output (V_{DC-DC})	Supplied Power to the grid (W_{Grid})	Phase Voltage (V_{AC})
0.23	1.961	0.23	47.6	27.6	120
0.32	2.941	0.32	49.5	38.4	120
0.57	3.922	0.57	51.4	68.4	120
0.68	4.902	0.68	53.3	81.6	120

Figure 4.5 shows the waveforms obtained from the oscilloscope as control voltage vary from 0 volt to 5 volt. The channel 1 waveform is the DC-DC converter output voltage and channel 2 is the current transducer output current generated from the grid connected inverter. The control voltage of the ADR101 linearly increases with the output voltage.

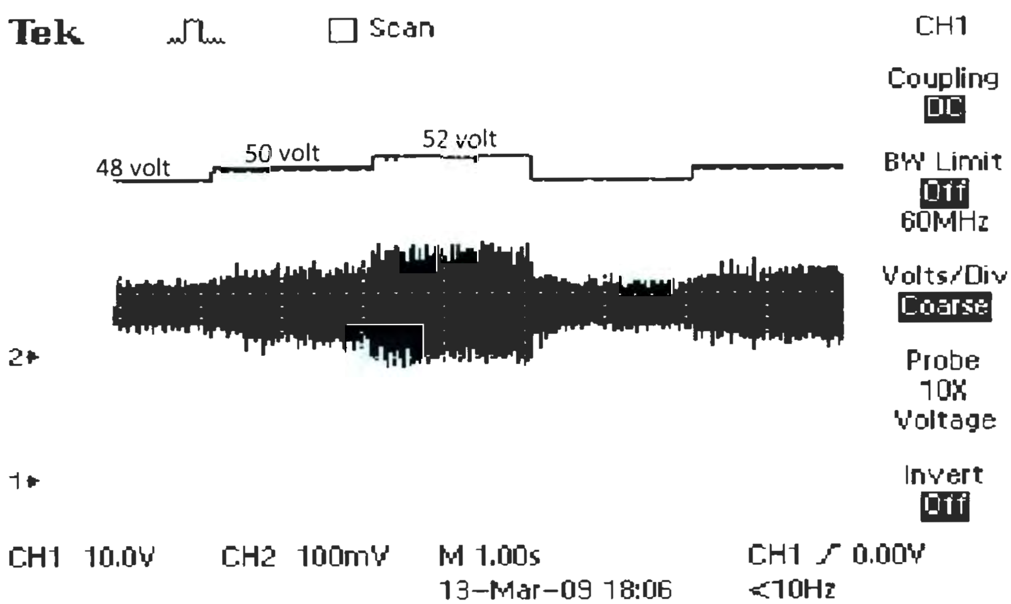

Fig. 4.5 DC-DC Converter and Current Transducer Continuous Output

Figure 4.6 shows the waveforms obtained from the oscilloscope at control voltage 3.9 volts. It is observed that the DC-DC converter's output voltage has decreased from 52 volts to 48 volts due to control voltage. The current transducer output also changed from 0.57 amps to 0.23 is shown in channel 2.

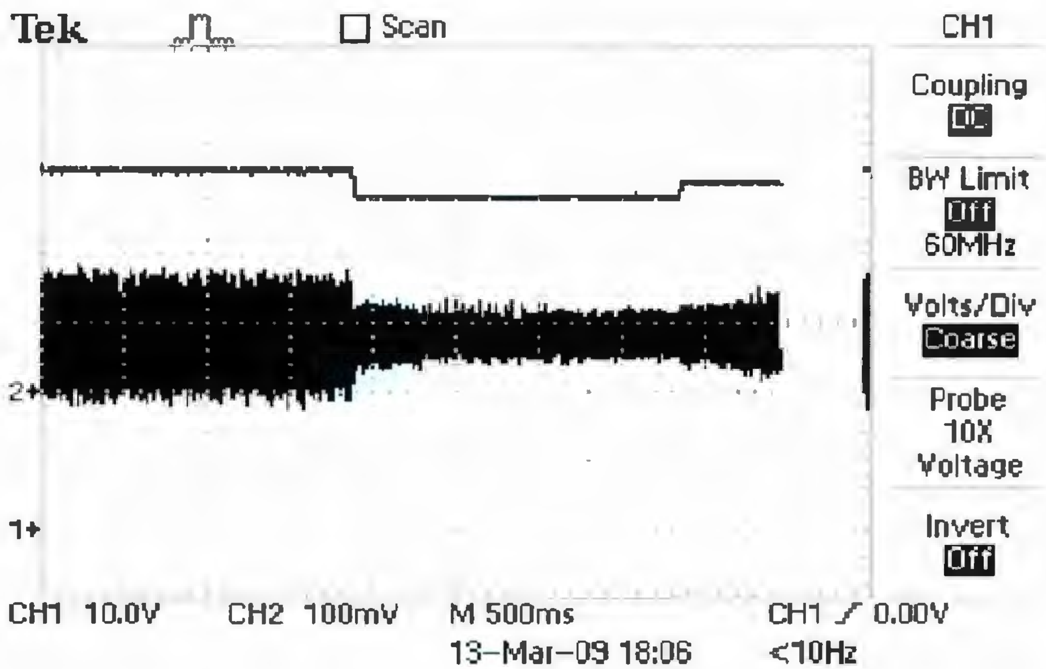

Fig. 4.6: DC-DC Converter and Current Transducer Intermittent Output

Figure 4.7 shows grid current increased from 0.23 amps to 0.32 amps which were close to the reference current. The 0.32 ampere is shown because the simulations for the model have been done for a reference current 0.32. The P controller simulated has a settling time of 1.5 sec but the settling time in real system was observed to be more than that. We need more instrumentation to more accurately observe the settling time and overshoot in the system.

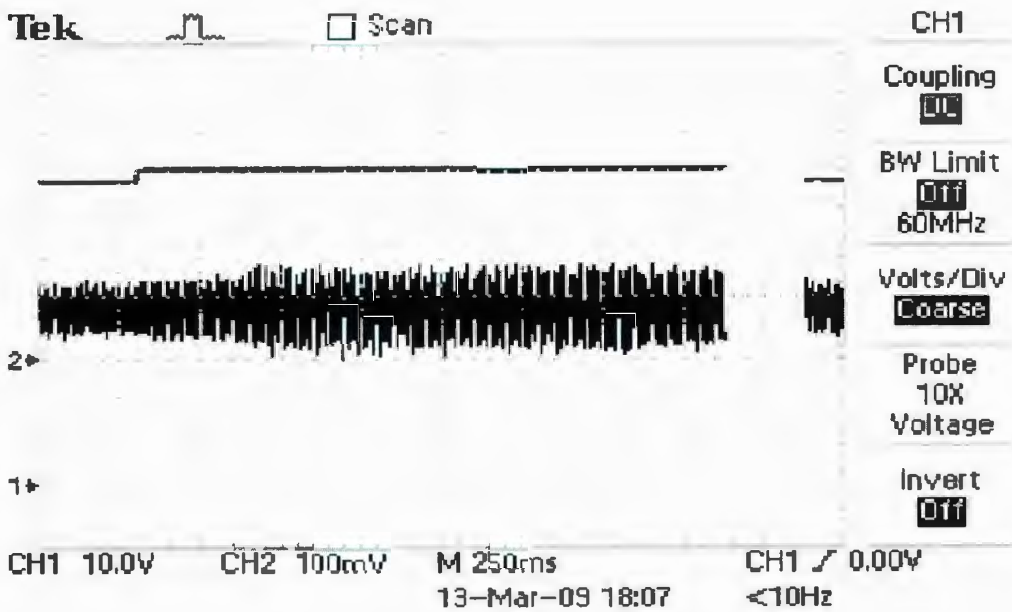

Fig. 4.7: DC-DC converter and current transducer intermittent output

Figure 4.8 shows the photograph of DC-DC converter, current transducer and oscilloscopes. These scopes were connected with the converter and the current transducer in order to monitor the output waveforms.

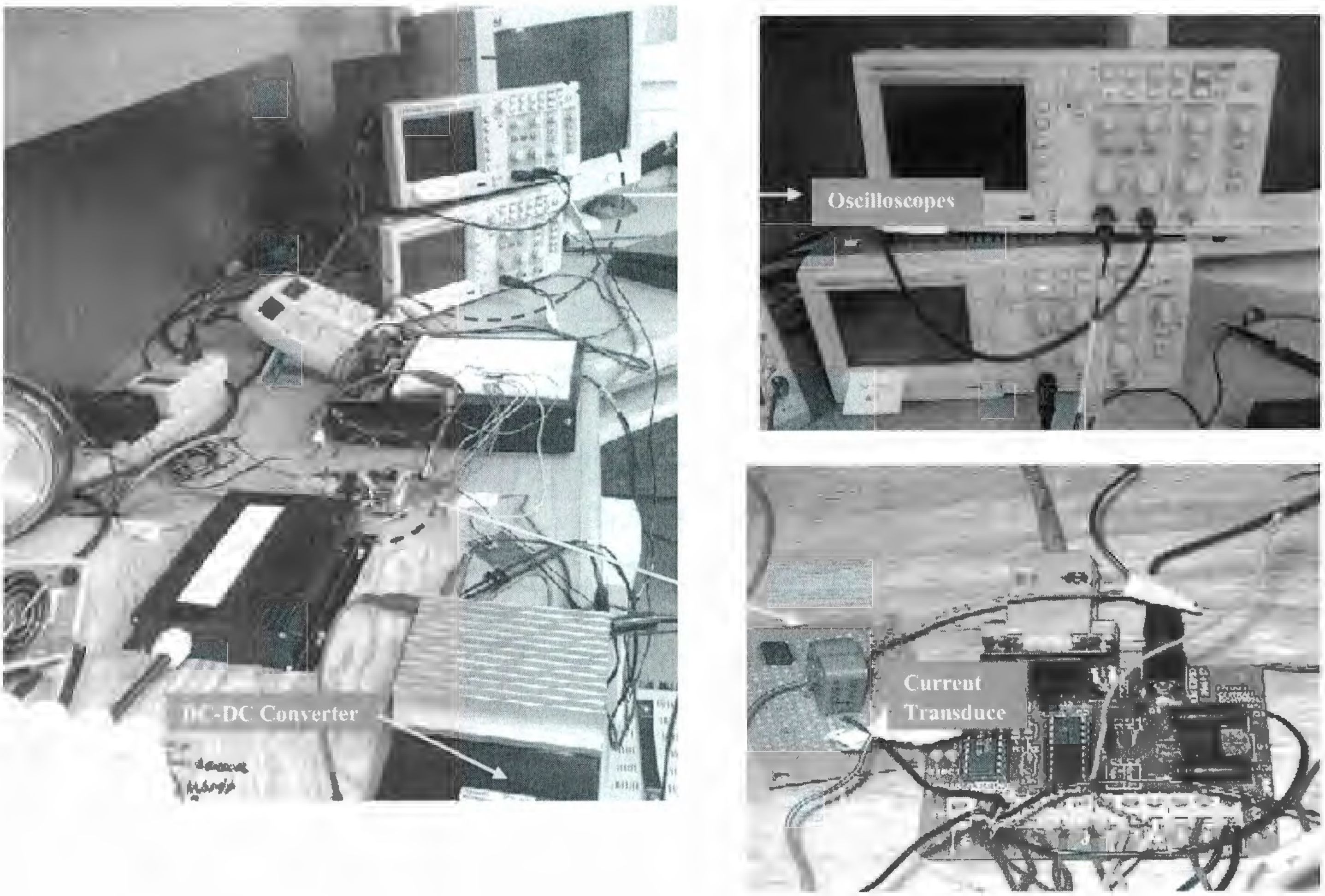

Fig. 4.8: Photograph of DC-DC converter, Current transducer and Oscilloscopes

4.3.2 Controller Based on Power Measurement

The control technique evolves on the measurement of power fed by the grid connected inverter to the grid. The experimental test results are shown in table 4.3. Table 4.2 shows inverter input voltage during the variation of DC-DC converter and power supplied to the grid.

Table 4.3: Inverter DC Input and Supplied Power to the Grid

Inverter input DC voltage $=V_{in}$	Power to the grid$=W_{out}$
47.6	27.6
49.5	38.4
51.4	68.4
53.3	81.6

At the very beginning inverter DC input voltage was 47.6 volts and power fed to the grid was 27.6 watts. As the DC input voltage increasing supplied power to the grid was also increased and it was 81.6 watts. Figure 4.9 shows power curve for the installed CPU of the inverter.

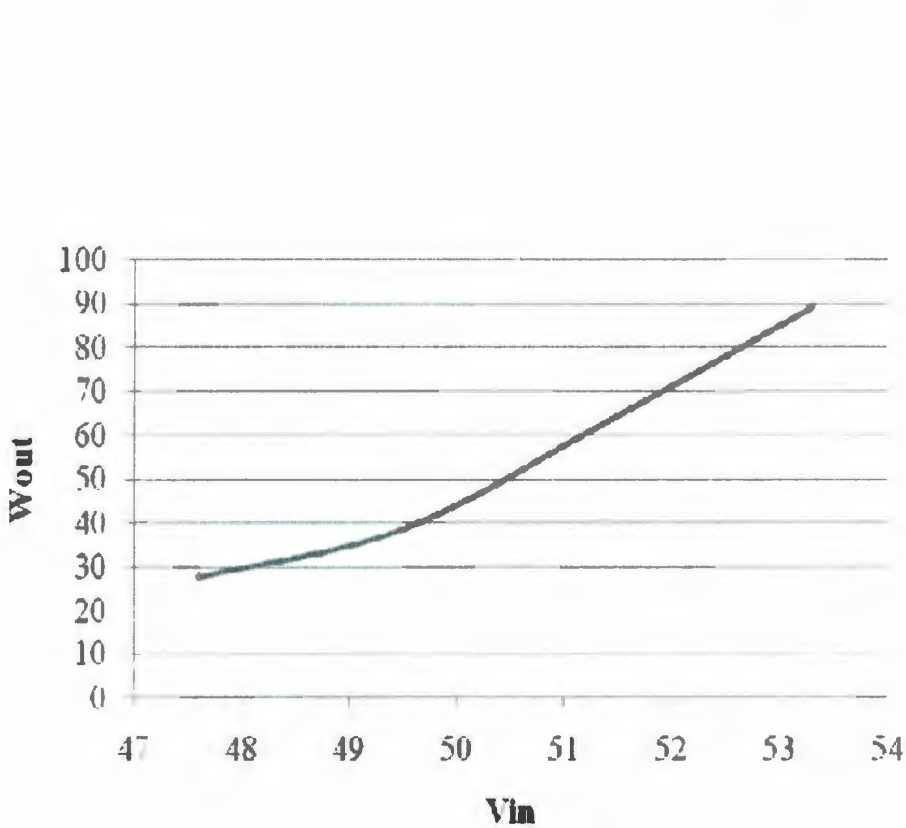

Fig. 4.9: Power Curve of the Inverter

4.4 Summary

Experimental and simulation results for the proposed remote control system have been presented in this chapter. Simulation of DG is performed by designing a P controller. The performance of the control system was investigated using a constant DC power supply in laboratory environment and using Matlab Simulink. The results prove the effectiveness of proposed method of remote control of DG system.

Chapter 5: Conclusions and Recommendations

5.1 Introduction

The main focus of this study was the development of a low cost remote control system for small grid connected inverter and distributed generation system (DG). An ADR101 controller is preferred as a controller which was programmed to make a grid tie inverter generation system operational and supply power to the grid. The controller operation was based on the reference control signal from dispatch centre (it was assumed that information is available in a file). An inverter based DG was also developed to provide the test platform of the proposed control system and associated instrumentation in laboratory environment. The summary of the proposed control system is described in the following sub-sections.

5.1.1 Grid connected Inverter

In the first phase grid connected inverter for distributed generation system such as wind turbine was implemented. The voltage verses power characteristic of the wind turbine was incorporated to a wind turbine inverter. To reflect the fixed speed of a wind turbine the DC power supply was considered. A control algorithm was implemented to control the system which ensures that the inverter follows the control signal from remote/dispatch centre. The test results on the inverter were performed at DC power supply and near to the control system which showed acceptable performance. Such an inverter is very effective in implementation of distributed generation system.

5.1.2 Feedback control system

In the second phase PC based control system was developed and tested to connect DC-DC converter and also maintain the connection between the generation system and the grid. The control system was developed for both control signals from dispatch centre vie internet and from an existing data file in a PC. In voltage feedback control system, DC-DC converter controlled the grid connected inverter output based on control voltage of the system. To protect the generation system and adjust voltage to the grid side, the control system always monitored the phase current between the inverter and the grid. The control system response was studied by observing phase current and inverter input. Test results were performed on feedback control system based on a DC power supply.

5.1.3 Controller Based on Power Measurement

Control system was implemented to connect the inverter with the grid. In this control method, PC received the required output power signal from a dispatch center via the Internet. The PC measured the power being fed by the inverter to the grid and used an ADR101 to control the dc-dc converter to adjust the power flow to the grid. TCP/IP link was used to access the ADR101. Power flow to the grid depended on the inverter input. The control system kept power supply to the grid until the inverter does not connect to the dump load. Power curve into the CPU provided quick response for maximum power out from distributed generation system. Investigations were carried out on this control system which showed the results as expected.

5.1.4 System Instrumentation

At this stage, low cost system instrumentation was developed and tested for the system controller. The purpose of the instrumentation was to measure the system parameters such as voltage from generation side, current and power flow between the inverter and the grid. Such instrumentation was very useful for reliable operation of the control system. Otherwise the improper design of the instrumentation may read incorrect parameter value which affect smooth operation of the control system.

The summary of outcomes of this research can be outlined as,

1. Instrumentation of a grid connected inverter provided a test bed for the control system.
2. A 250 watts grid connected inverter based remote control for distributed generation system was designed and developed. Two different techniques (laboratory environment and simulation) were implemented.
3. Development of instrumentation to measure the system parameters and tests were done to check the performance with the control system.
4. Design and test of the control system receiving reference command via internet.

5.2 Conclusions

The developed remote control system presented a novel remote control technique of a distributed generation system. In this thesis a remote control system which can be used for small grid connected inverter and DG system has been designed, tested and simulated. In industry it is hard to find a typical PC based remote system, and even when one is found it may not be economically feasible for a small lab to purchase. This thesis takes controller cost into consideration. In this thesis the traditional controller with DSP has been replaced with a low cost controller. In this thesis Proportional (P) control has been applied.

The Matlab simulations of the model for different reference current are shown. The output grid current are also obtained and compared to the experimental results. The simulations were performed by applying P control to track a reference current, and the results of such controls were discussed. The P control was implemented experimentally and compared to the simulation results.

The proposed system has presented good performance and capability for remote power control of a small grid connected inverter. The illustrated technique is also capable of remotely monitoring the system performance of the grid tie inverter and power control via the Internet from a dispatch center. A successful implementation of this system can be used to control remotely located distributed power generation system.

5.3 Future Work

In the developed remote control system, voltage verses power characteristics of the grid connected inverter are incorporated. The inverter was programmed only for one wind turbine. Therefore to reflect the real time behavior of the wind turbine, it is very significant to add the dynamics of the wind turbine. This requirement in a remote control system could make it more realistic which would be another good option to test the proposed remote control system for distributed generation system. In order to expand the power supply to the grid for high power applications the development of a control strategy to connect converters in parallel is required.

From the point of view of the software user interface, the number of monitored variables can be upgraded to meet specific demands (for example phase current and frequency). In order to improve the system performance and efficiency data transfer over the RS232 need to be studied. Furthermore, the control system is to be investigated for a grid connected inverter input voltage for over and under voltage condition. In addition, the control system is also needed to be further studied during abnormal frequency situation. The control system was expected to implement according to the installation standard described in chapter 2 which needs further improvement.

Publication List

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

Conference Papers

1. **Farhana Shirin**, Tariq Iqbal, "Remote Control of a Small Grid Tie Inverter", *Proceedings, Eighteenth Annual Newfoundland Electrical and Computer Engineering Conference (NECEC), November 6th, 2008,St. John's, Newfoundland.*

2. **Farhana S. Lina**, M. T. Iqbal, "Remote Control of Power Fed to the Grid in a Small Distributed Generation System", *Proceedings Canadian Conference on Electrical and Computer Engineering, May 6th, 2009 St. John's, Newfoundland.*

References

1. Distributed generation, The Institution of Engineering and Technology (IET), *www.theiet.org/factfiles*, available in 2008
2. Krismadinata Rahim, N.A. Selvaraj, J. "Implementation of Hysteresis Current Control for Single-Phase Grid Connected Inverter". *Int. Conf. on Power Electronics and Drive Systems*, 2007, Bangkok, pp. 1097-1101
3. Macken, K.J.P. "Control of inverter-based distributed generation used to provide premium power quality" *IEEE 35th Annual Power Electronics Specialists Conference, PESC04,* 2004, Aachen, Germany, pp. 3188-3194
4. S.R.Bull, "Renewable energy today and tomarrow," Pmc. IEEE.vol. 89, pp. 1216-1226. Aug. 2001.
5. H.B. Puttgen, P.R. MacGregor, and F.C. lambert, "Distributed generation: semantic hype or the dawn of a new era," *IEEE Power and Energy Mag.*, vol. I. pp. 22-29. Jan. /Feb. 2003.
6. T. Ackmnann, G. Anderson, and L. Sider, "Distributed generation: a definition." *Electric Power Systems Research,* vol. 57, pp. 195-204, Apr. 2001.
7. As the data collection processes have changed these figures may not be directly comparable.
8. *http://2008.energynetworks.comorg/distributed-generation*, accessed in 2008
9. F. Blaabjerg and Z. Chen, "Power electronics as an enabling technology for renewable energy integration," *J. Power Electron., Korean Inst. Power Electron.*, vol. 3, no. 2, pp. 81–89, Apr. 2003.
10. B. K. Bose, "Energy, environment, and advances in power electronics," *IEEE Trans. Power Electron.*, vol. 15, no. 4, pp. 688–701, Jul. 2000.
11. G. K. Andersen, C. Klumpner, S. B. Kjaer, and F. Blaabjerg, "A new green power inverter for fuel cells," in Proc. IEEE PESC, 2002, pp. 727–733.

12. B. K. Bose, P. M. Szczesny, and R. L. Steigerwald, "Microcomputer control of a residential photovoltaic power conditioning system," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 5, pp. 1182–1191, Sep. 1985.
13. Kojabadi, et. al, "A Novel DSP-Based Current-Controlled PWM Strategy for Single Phase Grid Connected Inverters", *IEEE Trans. on Power Electronics*, Vol. 21, No.4, July 2000, pp. 985-993
14. Authors: Silva, Sidelmo M.; Lopes, Bruno M.; Filho, Braz J. Cardoso; Campana, Rodrigo P.; Boaventura, Wallace C; "Performance evaluation of PLL algorithms for single-phase grid-connected systems" , *IEEE Industry Applications Conference*, 2004, USA, pp. 2259-2263
15. Papavasiliou, A.; Papathanassiou, S.A.; Manias, S.N.; Demetriadis, G.; "Current Control of a Voltage Source Inverter Connected to the Grid via LCL Filter" *Conference on Power Electronics Specialists,* 2007. pp. 2379 – 2384
16. Krismadinata; Rahim, N.A.; Selvaraj, J.; "Implementation of Hysteresis Current Control for Single-Phase Grid Connected Inverter" *Int. Conf. on Power Electronics and Drive Systems,* 2007. pp. 1097 – 1101
17. D. N. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady-state error," *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 814–822, May 2003.
18. R. Teodorescu, F.Blaabjerg, U. Borup, and M. Liserre, "A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation," in *Proc. IEEE Applied Power Electronics Conference and Exposition (APEC'04), Anaheim, USA*, Feb. 2004, pp. 580–586.
19. S. M. Silva, B. M. Lopes, B. J. C. Filho, R. P. Campana, and W. C. Boaventura, "Performance evaluation of PLL algorithms for single-phase grid-connected systems," in *Proc. The 39th IEEE Industry Application Society Conference and Annual Meeting (IAS'04), Seatle, USA*, Oct. 2004, pp. 2259–2263.
20. M. C. Benhabib and S. Saadate, "A new robust experimentally validated phase locked loop for power electronic control," *European Power Electronics and Drives Journal*, Aug. 2005, vol. 15, no. 3, pp. 36–48.

21. Zhang, X.; Ni, H.; Yao, D.; Cao, R.X.; Shen, W.X., "Design of single phase grid-connected photovoltaic power plant based on string inverters", *IEEE Conference on Industrial Electronics and Applications* , 2006, Singapore, pp.4025887
22. Zeineldin, H.H. El-Saadany, E.F. Salama, M.M.A. "Distributed Generation Micro-Grid Operation:Control and Protection". *Power Systems Conference on Advanced Metering, Protection, Control, Communication, and Distributed Resources,* 2006, pp. 105-111
23. Viawan, F.A.; Karlsson, D.; "Coordinated voltage and reactive power control in the presence of distributed generation" *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008 pp. 1 – 6
24. Prodanovic, M.; Green, T.C.; "Control of power quality in inverter-based distributed generation", *Annual Conference on Industrial Electronics Society, 2002 [IECON 02]*, pp. 1185 – 1189, vol.2
25. Cirrincione, Maurizio, Di Piazza, Maria Carmela, Marsala, Giuseppe, Pucci Marcello, Vitale Gianpaolo; "Real time simulation of renewable sources by model-based control of DC/DC converters", *IEEE International Symposium, June 30 2008-July 2, 2008, Cambridge, UK*, pp: 1548 - 1555
26. Padilha, Felipe J. C. Suemitsu, Walter I. Bellar, Maria D.; "DC-DC converter connected to three-level NPC inverter for renewable energy sources application", *IEEE International Symposium, Brazi*, 2008, pp: 264-269.
27. R. Pena, R. Cardenas, R. Blasco, G. Asher, and J. Clare, "A Cage Induction Generator Using Back-to-Back PWM Converters for Variable Speed Grid Connected Wind Energy System," *the 27th annual conference of the IEEE Industrial Electronics Society*, 29 Nov.-2 Dec. 2001, Vol. 2, Pages: 1376 - 1381
28. Teodorescu R., Blaabjerg F., "Flexible Control of Small Wind Turbines With Grid Failure Detection Operating in Stand-Alone and Grid-Connected Mode", *IEEE Transactions on Power Electronics,* Vol. 19, Issue 5, Sept. 2004 Page(s): 1323 - 1332
29. H. S. Patel and R. G. Hoft, "Generalized Technique of Harmonic Elimination and Voltage Control in Thyristor Inverter: Part I," *IEEE Transactions on Industry Application,* Vol. IA-9, Mar./Apr. 1973, Page(s): 310–317.

30. I. J. Pitel, S. N. Talukdar, and P. Wood, "Characterization of Programmed-Waveform Pulse-Width Modulation," *IEEE Transactions on Industry Applications*, Vol. IA-16, Sept./Oct. 1980, Page(s): 707– 15.

31. Fainan A. Magueed, and Jan Svensson, "Control of VSC connected to the grid through LCL filter to achieve balanced currents," in *Proc. IEEE Industry Applications Society Annual Meeting* 2005, vol. 2, pp. 72-578

32. M. H. Bollen, Understanding Power Quality Problems, Piscataway, NJ: *IEEE Press Series on Power Engineering*, September 1999

33. *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE Standard, 1547-2003, 2003

34. *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Standard 519-1992, April 12, 1003

35. Liserre M., Dell'Aquila A., Blaabjerg F., "Genetic Algorithm Based Design of the Active Damping for a LCL-filter Three-Phase Active

36. Rectifier," *IEEE Transactions on Power Electronics*, Volume 19, Issue 1, Jan. 2004 Page(s): 76 - 86

37. Macro Liserre, Frede Blaabjerg and Steffan Hansen, "Design and Control of an LCL-Filter-Based Three-Phase Active Rectifier", *IEEE Transactions on Industry Applications*, Vol. 41, No.5, Sept./Oct. 2005, Page(s): 1281 – 1291

38. Abeyasekera T., Johnson C.M., Atkinson D.J., Armstrong M., "Suppression of Line Voltage Related Distortion in Current Controlled Grid Connected Inverters", *IEEE Transactions on Power Electronics,* Volume 20, Issue 6, Nov. 2005 Page(s): 1393 – 1401

39. Tunlasakun, K. Kirtikara, K. Thepa, S. Monyakul, V., "A microcontroller based islanding detection for grid connected inverter" *47th Midwest Circuits and Systems Symposium,Thailand,* Volume: 3, Issue 25-28, July.2004, page(s): iii - 267-9 vol.3

40. *http://www.duxlite.com/grid.htm* accessed in 2009

41. *http://www.ginlong.com/grid-tie-connected-inverter- controller.htm* accessed in 2009

42. S. Ali Khajehoddin *§, Praveen Jain*, and Alireza Bakhshai* "A string grid-connected converter topology for photovoltaic systems " *Energy and Power Electronics Applied Research Laboratory (ePEARL), Queen's University, Canada

43. T. Shimizu, K. Wada, and N. Nakamura, "A flyback-type single phase utility interactive inverter with low-frequency ripple current reduction on the DC input for an AC photovoltaic module system," vol. 3, pp. 1483–1488, 2002.
44. S. B. Kjaer and F. Blaabjerg, "Design optimization of a single phase inverter for photovoltaic applications," vol. 3, pp. 1183–1190, Jun. 2003.
45. Electricity, electricity feed laws, feed-in tariffs, and advanced renewable tariffs. Technical report, www.wind-works.org/articles/feedlaws.html, last accessed 2009
46. M.T. Iqbal. A small induction generator based grid connected wind turbine simulator. St. John's, NL, November 2005. *15th IEEE Newfoundland Electrical and Computer Engineering Conference.*
47. M.P. Papapoulos, 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.*
48. T. Petru and T. Thiringer, editors. *Active Flicker Reduction Form 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
49. Liviu Mihalache, and Mihai Chis, "DSP Control Improves Inverter Performance and Density" published in Power Conversion Technologies Inc., Harmony, Pa, Feb 1, 2003
50. Ismail, B. Taib, S. Saad, A.R.M. Isa, M. Hadzer, "C.M Development of a Single Phase SPWM Microcontroller-Based Inverter" Power and Energy Conference, 2006. PECon '06, Putra Jaya. page(s): 437 - 440
51. Serial Data Acquisition and Control Interface, available at *http://ontrak.net/ADR101.htm* accessed on 2008.
52. ComPAC Family 50-600 Watt DC-DC Power System, available at *http://www.hy-line.de*, accessed on 2008.
53. K. Ogata. Modern Control Engineering, 4 edition, 2002