A Small Induction Generator Based Grid Connected Wind Turbine Simulator

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Abstract

A number of types of small wind turbines are available in the market. Such wind turbines are primarily designed for isolated operation. The available small wind turbines are based on permanent magnet type generators or field regulated alternators. A common application of such wind turbines is battery charging. 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 a dump load. This option is not cost effective mainly because of the high cost of the power electronics, batteries and ongoing maintenance cost of the battery bank. An induction generator based wind turbine that meets all the requirements of the IEEE 1547 standard would be the best low cost option for households. This paper describes the design and development of a drive train and a controller for a small induction generator based wind turbine. The paper focuses on a wind turbine simulator developed to help design and test the proposed induction generator based wind turbine. The wind turbine simulator consists of a Labview based computer controlled DC motor, a three-phase induction generator, instrumentation for voltage, current, torque and speed measurements. The paper describes the first version of the wind turbine controller that is based on speed measurement and a soft starter. System design, initial test results and future directions are described in the paper.

Introduction

Wind energy development in the world is growing at a rate of almost 40% per year [1]. There are over 55000 large wind turbines installed today employing more than 70,000 people worldwide. As of July 2005 Canada's installed wind energy capacity was 570 MW [2]. Canada has large utility-scale wind turbines installed in Alberta, Saskatchewan, Ontario, Quebec, Prince Edward Island, Nova Scotia and the Yukon. Canada has a national wind resource map accessible at www.windatlas.ca. Canada could reasonably meet 20% of its total energy needs with wind power [2]. Canada has the ability to manufacture utility-scale wind turbine components, such as blades, towers and nacelles. However, within Canada there are currently no manufacturers of generators, gearboxes and control systems, nor any comprehensive wind turbine manufacturing facilities. Canadian Wind Energy Association has recently started a major initiative on small wind energy (300W-300kW). Details may be found at www.smallwindenergy.ca

The wind turbine market place can be viewed in three tiers. The first tier involves large utility grade machines, which are between 250kW and 5MW machines. Most wind power is produced by these machines, which are typically installed in large farms. Utility grade wind power accounts for most of the worldwide capacity. The second tier includes mid sized machines from 20kW to 250kW and is typically grid connected machines in remote communities. This middle market has not matured into any particular use pattern. The third tier includes machines smaller than 20kW, and goes down to around 300W. These machines are used for individual residential use, remote site power, recreational marine power and water pumping [3].

Canada has an immense wind energy resource that can be tapped. There is great interest in wind energy amongst the general public especially people living in rural and remote areas. People living in remote communities often pay rates as high as $0.20 per unit for diesel generated electricity. Installation and use of medium and large systems need considerable investment and is done by power producing utility companies using a commercial utility interconnect. In contrast, small wind machines are installed by homeowners, farmers and small businesses, typically using a grid tie inverter connected to the smallest edges of the power grid. This generating architecture is known as 'distributed' or 'micro'. A number of types of small wind turbines are available from various manufactures [3,7]. Such wind turbines are primarily designed for isolated operation. Small wind turbines are based on the permanent magnet type generators or field regulated alternators. Common application of such wind turbines is battery charging. Such wind turbines may be connected to the grid using commercially available grid tie inverters, in combination with a charge controller, battery, and dump load [8,9,10]. If a person living in a village or out of town wants to generate some electricity using wind energy their only option is a combination of small wind turbine, battery storage, charge controller, dump load and a grid tie inverter. This option is not cost effective mainly because of high cost of power electronics and batteries and ongoing maintenance of the battery. The Gridtek inverter from Bergey is a single exception, where the inverter uses an AC➔DC➔AC architecture for connection to the grid, the machine is still expensive and does not meet standards such as IEEE 1747 [4].

Small power production (Micro or Distributed) is being encouraged by the introduction of net metering regulations. This option is already available in 34 states in US and in parts of Ontario and Manitoba. New standards and laws regulating such micro production are being developed and implemented. In the US, recently, the Institute of Electrical and Electronics Engineers approved its new standard IEEE 1547 for interconnecting distributed energy resources to the power system. IEEE 1547 supercedes the older IEEE 929 standard. An equivalent standard for Canada is being worked on and will be implemented in the near future [4,5]. In the near future, net metering option will also become available to every one in Canada. This will open a great opportunity to reduce power bill for people living in villages and outside of towns.

The existing grid in rural communities is single phase. A transformer near the houses converts single phase to 2-phase. A typical house has 2-phase input 120V, 200A each. Most of the electrical load in the house is single phase. In a net metering situation if a person wishes to produce small amount to electricity, say 5KW, using a wind turbine then the best option is to produce as 1-phase 120/220V. Typical house energy consumption in Canada is 2.8kW. A 3kW small grid wind turbine can bring down the power bill significantly. If a wind turbine is suitably selected the net energy consumption in a house over a year may be zero [6]. Such an option would be a great attraction for people living in villages and around small towns.

In this research we have developed a small wind turbine drive train based on a high slip induction generator that is directly connected to the grid. A wind turbine controller being developed make sure that this wind turbine meets all requirements of the IEEE 1547 and Micro power connect interconnection guideline being developed for Canada. This paper describes the system under development and some primary test results.

Wind Turbine Simulator and Controller

We are building a wind turbine drive train driven by a variable speed dc motor. The main purpose of this drive train is to design and test of wind turbine controller. Figure 1 shows a block diagram of the small wind turbines drive train. The drive train consists of an ac to dc converter, a DC motor, an Induction generator, solid state relays and control electronics. Presently a PC with Labview is being used for system control and testing. Later we will design and build a microprocessor-based controller to control the system in various situations. A rechargeable battery will power the system's microprocessor based controller, frequency circuit and sync circuit. The battery will be charged using generated power from the system.

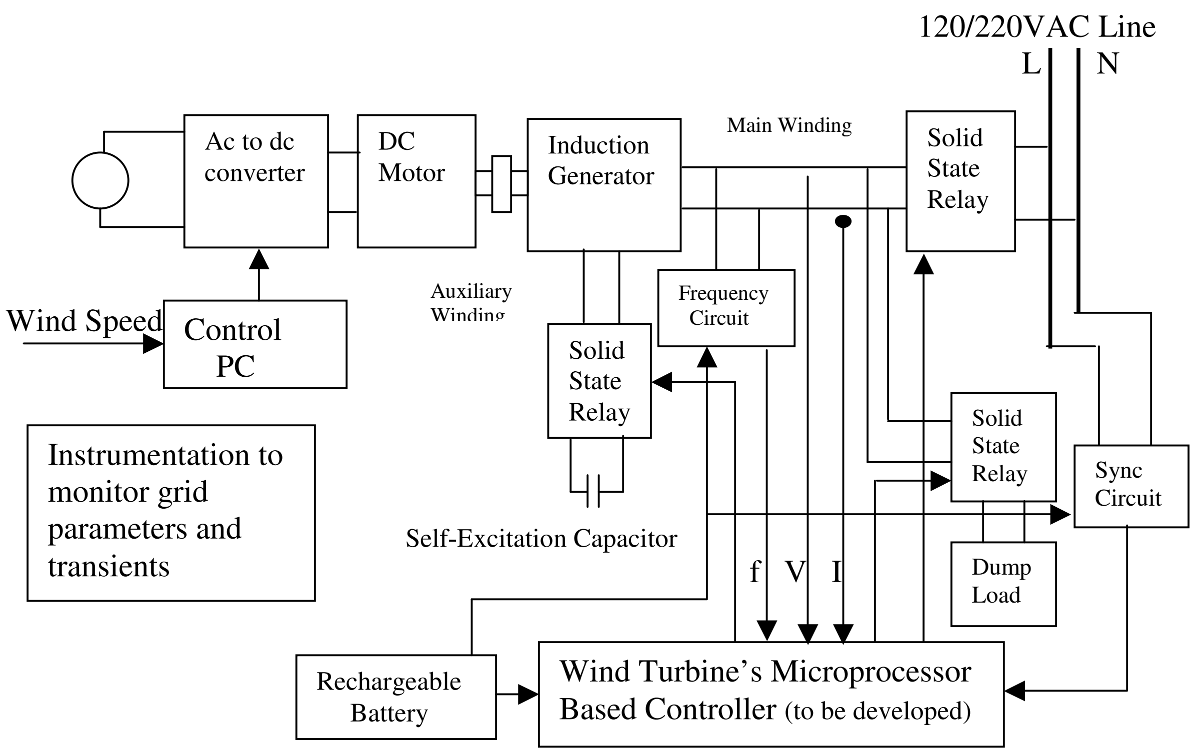

Figure 1.0 Block diagram of proposed small wind turbines Simulator

A typical control sequence of the wind turbine controller may occur as follows. Assume a low wind, generator disconnected from the grid and turbine running at a low speed. As the wind speed picks up, the generator speed will increase and its output signal frequency will also increase. The generator is not self excited yet, therefore it will only produce a small signal due to its remnant magnetism. The system controller will sense the generator output via the frequency circuit and it will also receive a sync signal from the grid through the sync circuit. When the generator output frequency is about same as the grid frequency solid-state relay will operate and the generator will be connected to the grid. After that, the controller will monitor the current flow between the grid and induction generator. If current is positive i.e. power going to the grid, then controller will maintain the grid connection. If current goes negative i.e. generator switch to motoring mode, then controller will disconnect the generator from the grid. This may happen due to a drop in the wind speed. The controller will keep monitoring the grid and generator output. If after some time, the generator output frequency approaches the grid frequency the controller will reconnect the system to the grid. This operation will repeat depending upon the wind speed and availability of the grid. A hysteresis band will be used in the control algorithm to reduce the number of switching. Dump load will be used when wind is available but the grid is not available. On a windy day if grid is not available, then after observing the frequency signal, the controller will attach the self-exciting capacitor to the auxiliary winding of the induction generator. The controller will observe the voltage and current output of the generator. If the voltage exceeds a certain limit (due to generator speeding up) the controller will connect the dump load to the generator by operating a solid-state relay. This will make sure that wind turbine does not over speed due to soft stall [11]. The controller will connect and disconnect the dump load as required on the basis of current and voltage measurement to make sure the system operates safely. If grid becomes available then controller will disconnect the dump load and connect the generator back to the grid. The decision whether to maintain or not to maintain grid connection will be based on the generator current from its main winding.

In the lab environment, as shown in the figure 1.0 the induction generator will be connected to a variable speed DC motor. This setup is required to test and finalize the controller design. During the testing phase induction generator will operate in the variable speed mode using the DC motor and various system signals as well as grid parameters will be recorded. Controller design will make sure the system meets the Micropower Connect Interconnection Guidelines [4, 12, 13, 14]. For example, on a windy day in the event of grid failure the system will disconnect within 2 cycles if voltage is more than 137% or it will disconnect within 6 cycles if voltage is less than 50%. Wind turbine system induced grid voltage and current transients will be recorded in all possible situations to make sure system meets micropower connect interconnection guidelines and new IEEE 1547 standard. System based on 5hp induction machines will be tested on a standard 60A utility outlet [13]. An off the shelf microprocessor and development PCB will be used to build the controller for the generator system. This approach will allow for rapid prototyping of the controller and low cost reconfiguration of connections to allow for maximizing performance of the system. The controller application will be coded according to a state transition map. As such, the application can be coded in any language with sufficient semantic expression, such as C, C++, assembly or others.

Progress So Far

Small wind turbine simulator is based on Mawdslay's multiform experimental setup. A photograph of the system is shown in figure 2.0 It consist of a 3kW, 120V shunt type DC motor, a tacho meter, a torque transducer and a experimental machine. The experimental machine can be connected as 2/4 pole basic dc machine or 2/4/6/10/12/14 pole 3-phase induction/synchronous machine or A.C. commutator machine or single phase induction motor. Presently, it is connected as 4-pole, 4 coils in parallel, 3 phase, Y-connected induction motor with the rotor winding shorted by a shorting ring (sheet 11). It was connected in this way to achieve voltage levels of 120/208V while running at about 1800rpm so that it can be connected to the grid. The DC motor is armature controlled with a fixed 76V field supply. Controlled variable DC voltage for the DC motor is obtained using a phase controlled relay and a bridge rectifier. Coupled 3-phase induction generator is connected to the grid using a two relays based soft-starter. Generator current, voltage, speed and mechanical torque are measured. Figure 3 shows details of instrumentation electronics. A PC controls the system with a NI 6024 data acquisition card and Labview 5.5 PC measures system speed, current, torque and voltage and controls two relays. When system speed is about 1800rpm PC first connects the generator to the grid-using relay R2. Series power resistors limit the surge current. After a delay of few seconds PC switches on relay R1 so that the generator is connected directly to the grid. The generator is disconnected from the grid if current drops to zero and stays for some time.

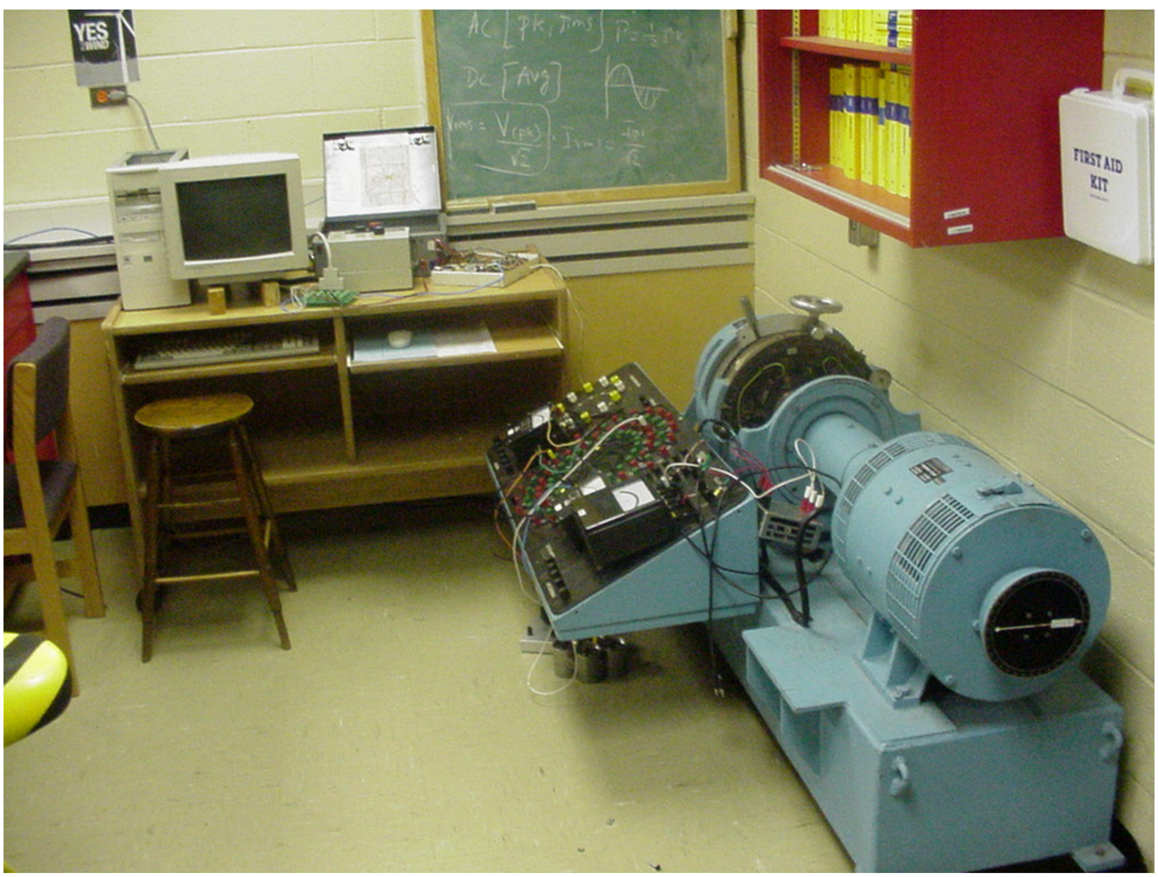

Figure 2: A photograph of current wind turbine simulator

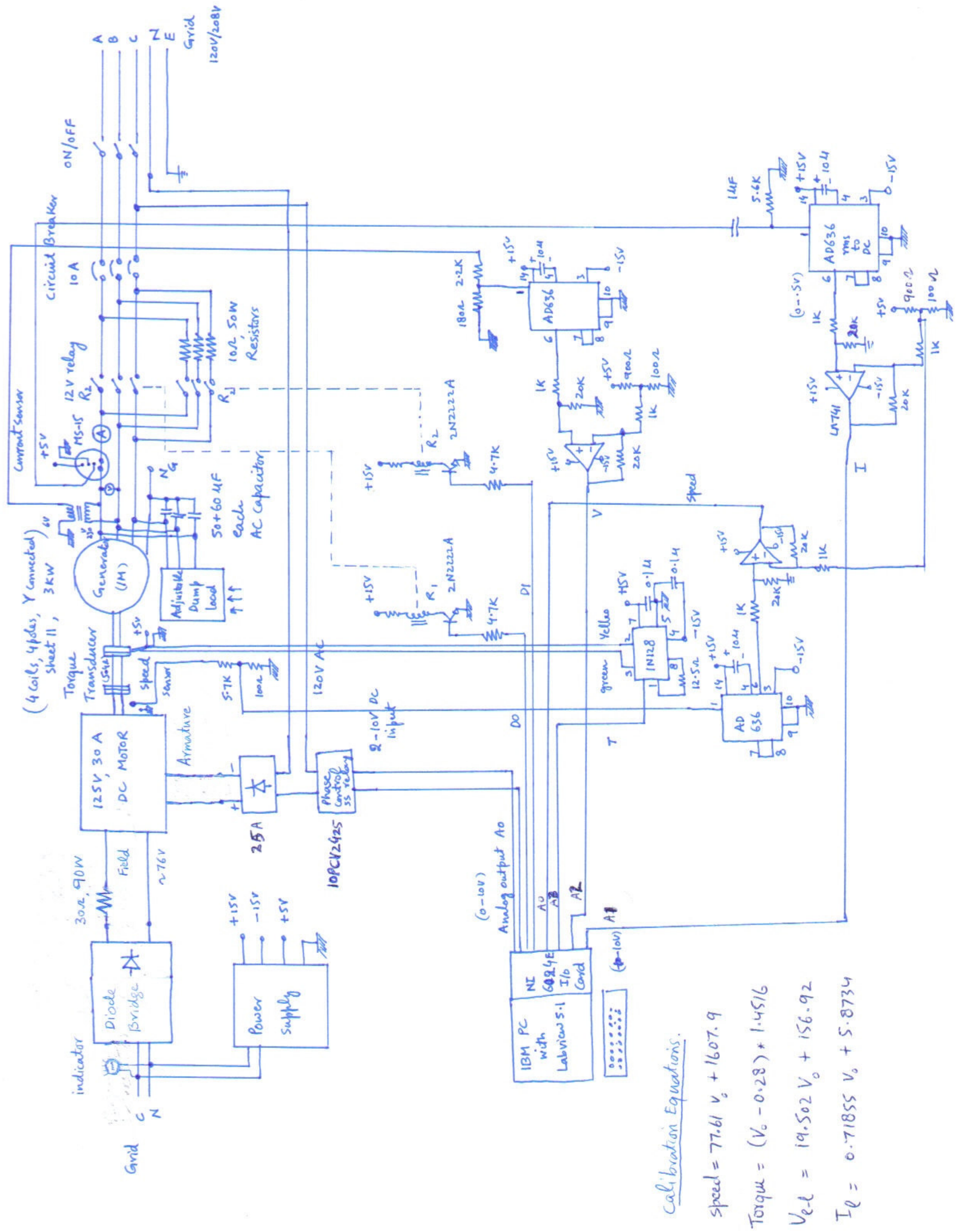

Figure 3: Instrumentation details of WT simulator

The system calibration equations are also provided in figure 3. The system can be controlled in manual mode or in auto mode. Figure 4 and figure 5 show Labview control diagrams in manual and in auto mode. In manual mode DC motor speed is controlled using a virtual knob and relays can be engaged or disengaged using mouse. All calibration equations are embedded in the Labview code so that display window provides a calibrated display. In auto mode DC motor speed is controlled based on the pre-recorded wind speed data stored in a file. This is shown in figure 5. Based on the current rotor speed and wind speed the tip speed ratio is calculated. Present tip speed ratio is used to calculate the desired torque. When the system is connected to the grid its speed is determined by the grid frequency. In this case the shaft torque is adjusted to make sure that the system is running at an optimum tip speed ratio. Motor speed is regulated such that the system is running at the optimum tip speed ratio. A PID controller ensures that the system is at optimum tip speed ratio. Grid connection and disconnection decisions are based on speed and current measurements. PID controller parameters can be adjusted on the Labview main screen. Essentially in auto mode, based on the prerecorded wind speed data and system model the DC motor is controlled in such a way that it represents a 3kW wind turbine rotor. It will produce a shaft torque same as a real wind turbine rotor running in the wind.

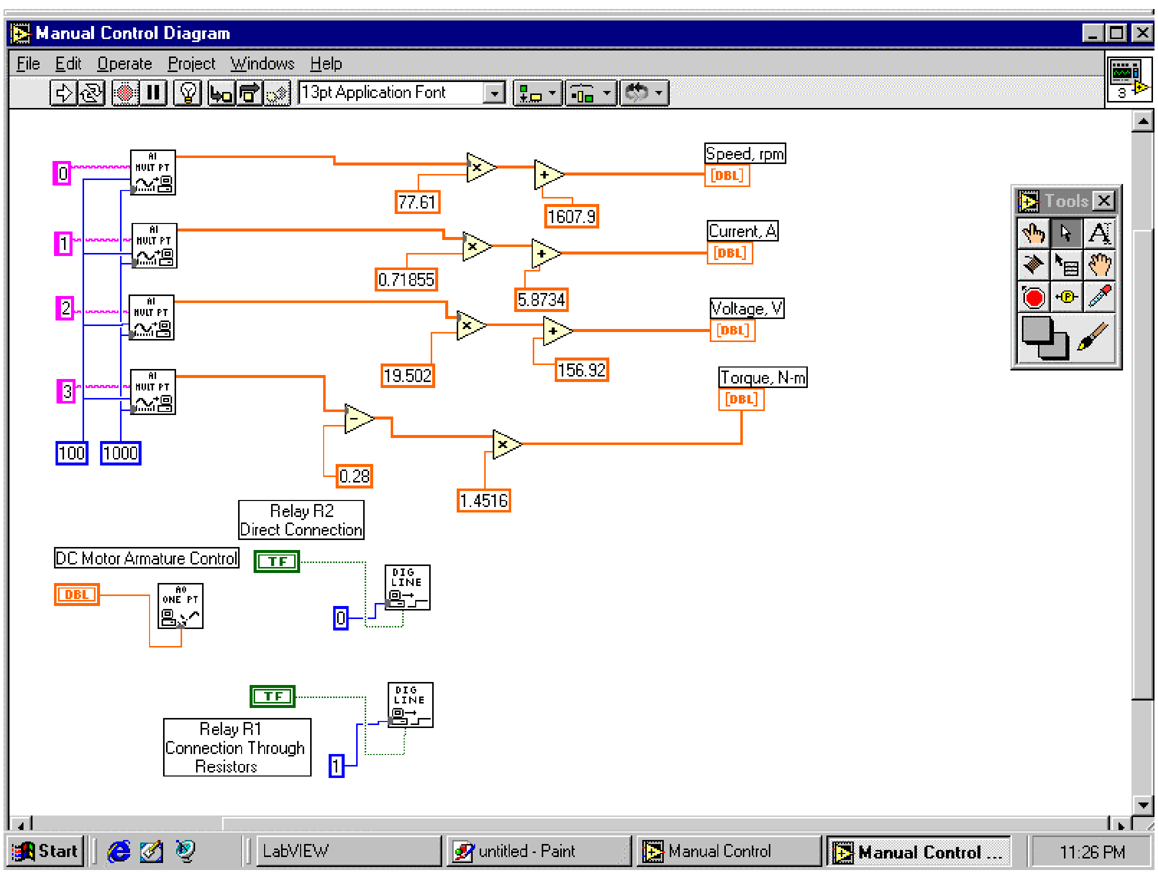

Figure 4: Labview control diagram for manual control of WT simulator

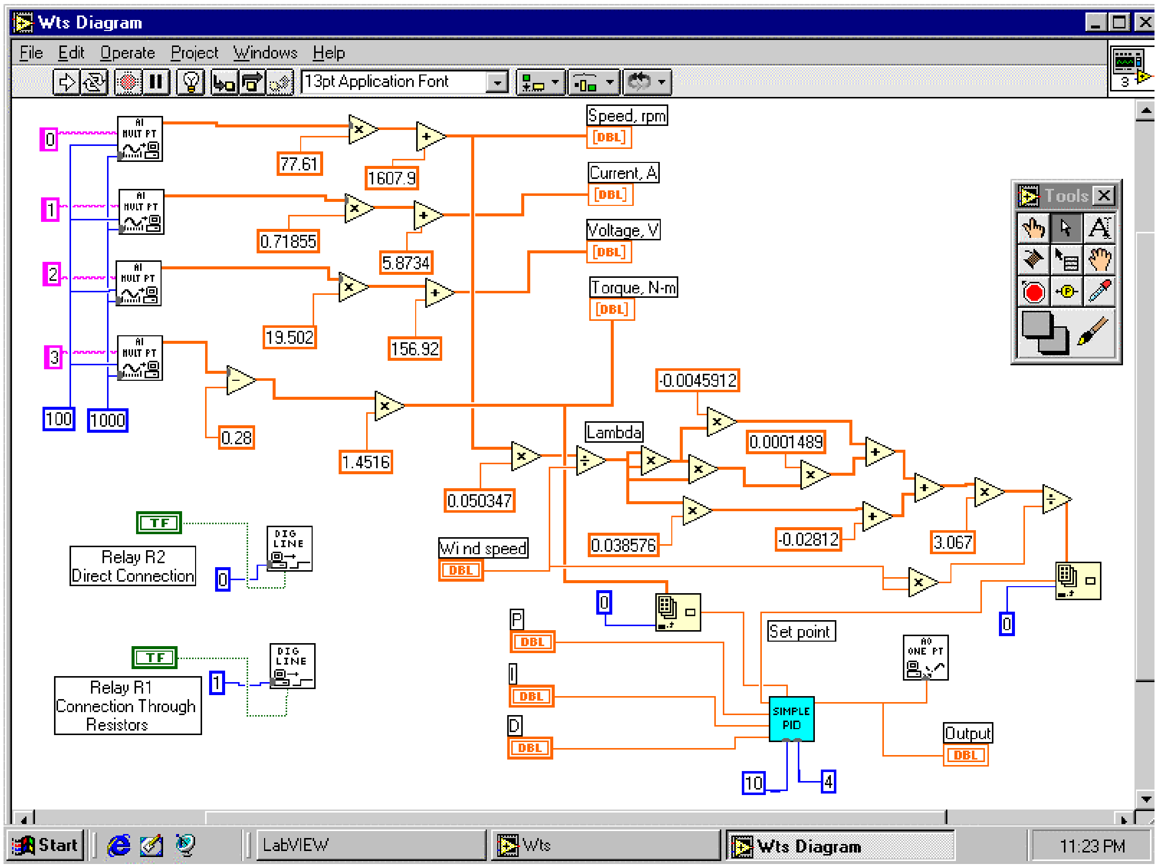

Figure 5: Labview control diagram of WT simulator

In other words squirrel cage induction generator will behave as if a wind turbine drives it. With such a setup at hand we can work on the wind turbine controller design and test that in the lab arrangement. Presently, a PC function as the wind turbine simulator and the controller. Figure 6 shows PC screen shot while system is under going a test. System speed, voltage, current and torque are displayed on the screen. Grid connection and disconnection transients can be studied using this setup. Eventually as shown in the figure 1 a microprocessor-based controller will be designed to control the system. That controller will make sure that system meets the IEEE 1547 standard. i.e if its voltage is below 50V or above 120V then it disconnects in 0.16s, if voltage is more than 50V but less that 88V then it disconnect in 2s, if voltage is more that 110V and less than 120V then it disconnect in 1s. Similarly controller will also look at the frequency and make sure that it is with in the range specified in the IEEE 1547 standard. Wind turbine simulator describe above will help design and test the proposed wind turbine controller.

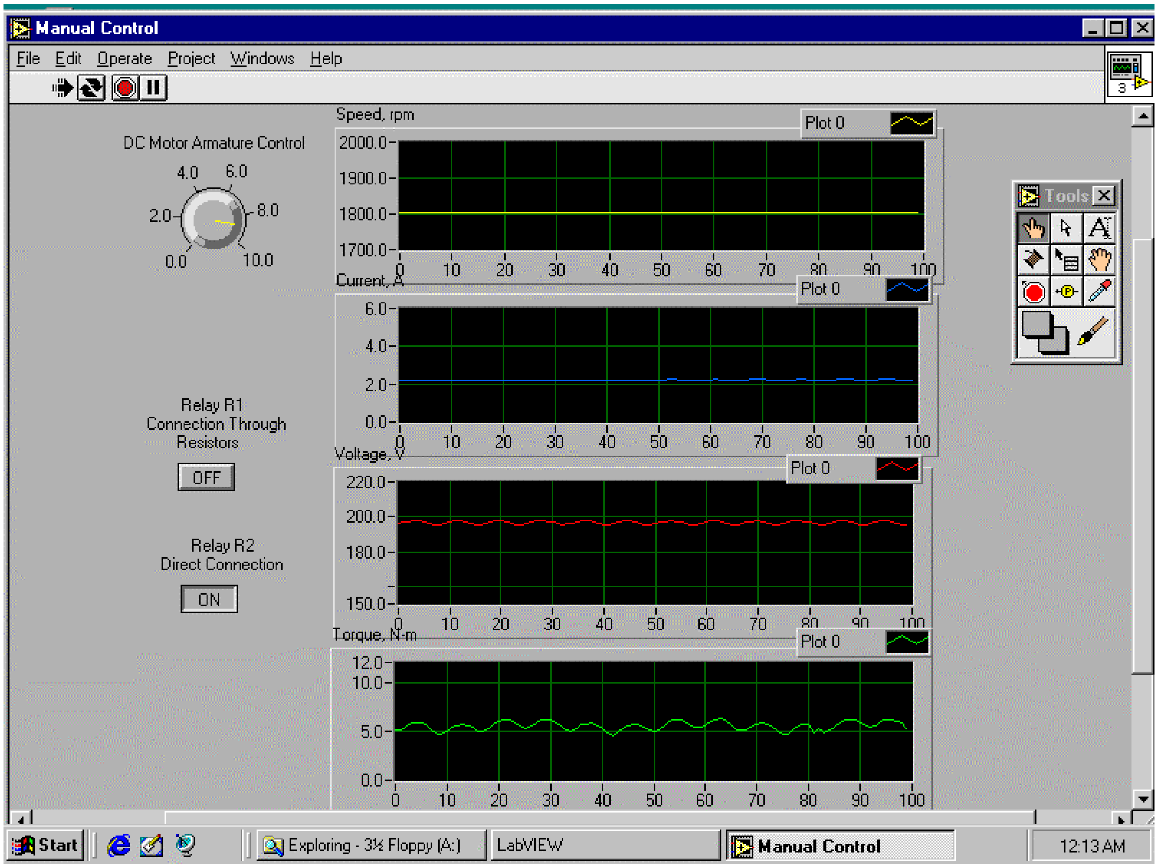

Figure 6: Labview output during testing

Primary Test Results

The wind turbine simulator setup described above has been used to test a wind turbine controller. Figure 7 and 8 shows some primary test results. Figure 7 shows what happens to the generator speed and current when the induction generator running at about 1800rpm is connected to the gird through a soft-starter. As soon as the generator is connected to the grid through series resistors its speed decreases and there is a current surge. The resistors limit current surge. After few seconds when it is directly connected to the grid its speed becomes a constant. This test can be used to identify the suitable series resistors and time delay between operations of two relays. Figure 8 shows what happen to the generator speed and current when it is disconnected from the grid. As soon as induction generator is disconnected from the grid its speed increases and current decreases. Such test can be used to find out the expected over speed spikes in the wind turbine. In the near future further testing will be done on the system to determine the following:

1. Best PID controller parameters for the wind turbine simulator
2. Suitable value and power rating of soft starter resistors (Presently it is 50W, 15Ω)
3. What is the suitable time delay between the operation two relays
4. How to automatically make decision about grid connection on the basis of speed and about grid disconnection on the basis of current

5. Design a microcontroller based system controller
6. Study the impact of connection and disconnection of small induction generator based wind turbine on the grid.
7. Test wind turbine simulator and newly designed controller in a variety of possible real time situations.

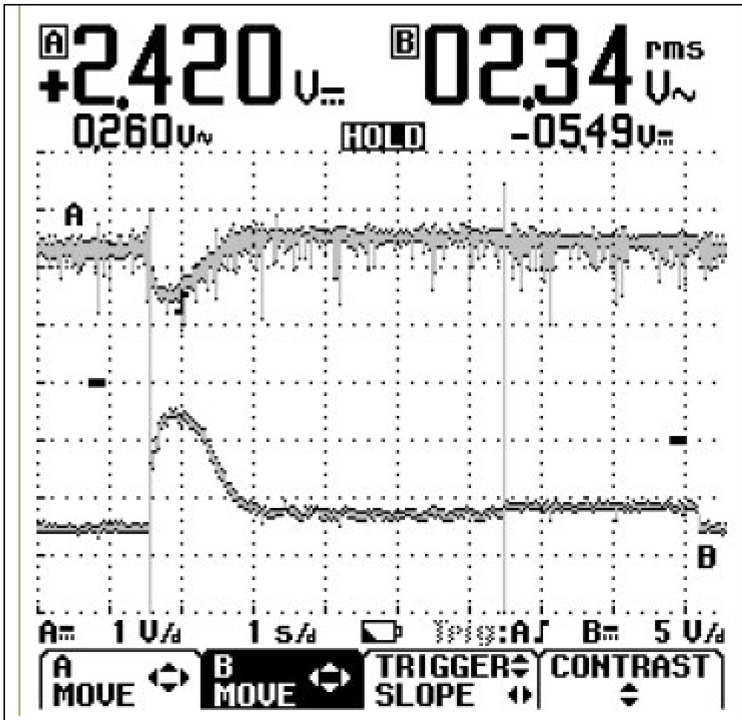

Figure 7: System response at grid connection. Channel A is speed while channel B is Current

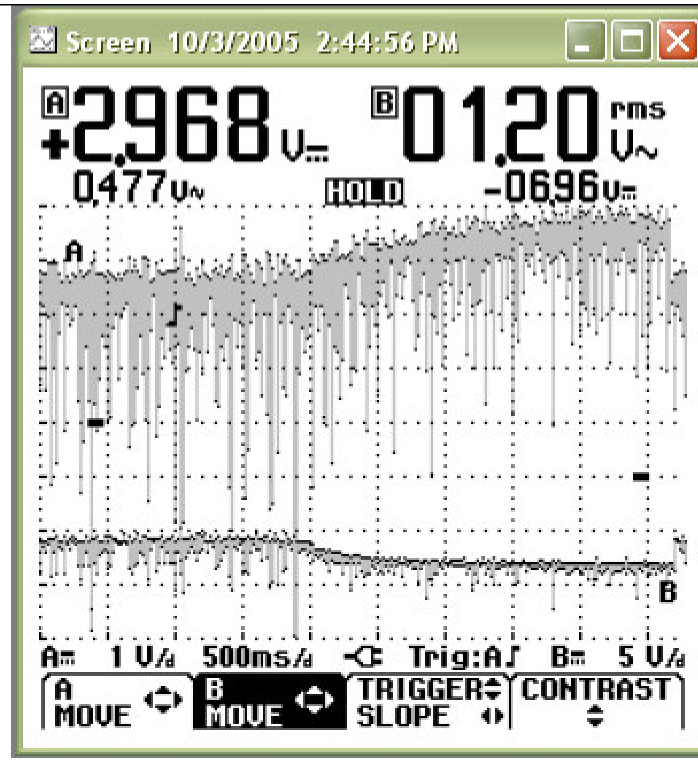

Figure 8: System response at grid disconnection. Channel A is speed while channel B is Current

Conclusions

This paper described design and development of a wind turbine simulator and a controller for a small induction generator based wind turbine. The paper reports the progress made so far. The designed wind turbine simulator consists of a Labview based computer controlled DC motor, a three-phase induction generator, instrumentation for voltage, current, torque and speed measurements. The paper also described the first version of the wind turbine controller that is based on speed measurement and a soft starter. Primary test results are presented. It appears that a small wind turbine will have no significant effect on the grid while connecting or disconnecting from the grid. Simulator being developed is a great tool to design and develop induction generator based grid connected wind turbine.

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References

1. Zervos A. and Teske S., 'Wind force 12: How wind could provide 12% of the world's electricity by 2020', Renewable Energy World, pp 73-89, July-August 2002.
2. Canadian Wind Energy Association. http://www.canwea.ca
3. Manufacturers of Small wind turbines, American Wind Energy Association. (http://www.awea.org/faq/smsyslst.html)
4. http://www.micropower-connect.org
5. Chang, L., 'Wind energy conversion systems,' IEEE Canadian review, spring 2002
6. Iqbal, M.T., 'A feasibility study of a zero energy home in Newfoundland,' Renewable Energy, Vol. 29, No.2, pp 277-289, 2004
7. Sagrillo, M., 'Apples & Oranges 2002 - Choosing a Home-Sized Wind Generator,' Home power, August/Sept 2002
8. Rogers, A. L., Manwell, J. F, and McGowan, J. G., 'Design requirements of medium sized wind turbine for remote and hybrid power systems,' Renewable energy, Vol. 26, No. 2 pp 157-168, 2002.
9. Corbus, D., et al, ' Small wind turbine testing and applications development,' Proceedings of Wind power 99, Burlington, Vermont, June 20-23, 1999.
10. Clausen, P.D., and Wood, D. H., ' Recent advances in small wind turbine technology,' Wind Engineering, Vol. 24, No. 3, pp 189-201, 2000
11. Muljadi, E., Forsyth, T., and Butterfield, C.P., ' Soft-stall control versus furling control for small wind turbine power regulation,' Proceedings of Wind power '98, Bakersville, CA April 27-30, 1998.
12. Machado , R. Q., Marra., and E. G., Pomilio., 'Bi-directional Electronic interface of induction generator connected to a single phase feeder,' International Journal of Renewable Energy Engineering, August 2002.
13. Dubois, M., 'Comparison of generator topologies for direct-drive Wind Turbines, IEEE Nordic Workshop on Power and Industrial Electronics (NORPIE/2000), Aalborg, Denmark, June 13-16, 2000.
14. Sharma, H. Islam, S., Pryor, T. and Nayar, C.V, 'Power quality issues in a wind turbine driven induction generator and diesel hybrid autonomous grid,' Journal of electrical and electronics engineering, Australia, Vol. 21, No. 1, pp 19-25, 2001