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Design and Implementation of controller for Wind driven PMSG based Standalone System

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Abstract: The main aim of the project is to use an ac/dc/ac power converter to extract power from variable speed Permanent Magnet Synchronous generator (PMSG) and feed it to supply a standalone load. The output voltage and frequency of the PMSG is variable in nature due to non uniform wind velocities . In order to condition and feed it to a load we need power electronic interface. The variable three phase ac output at the PMSG is rectified by a diode rectifier and the dc link is maintained constant by a boost converter. The boost converter is provided with a closed loop feedback control, which is designed using PI controller. In this controller the output voltage is continuously sensed and duty ratio of the switch is varied to maintain the DC output voltage. The converter output is fed to 3 phase inverter which employs a sine PWM technique, the output of which can be fed to a load or grid. The inverter is incorporated with both real and reactive power control to match the grid or load specifications. The power converters and together with independent control systems can effectively improve the output voltage and frequency of the wind PMSG feeding an isolated load. The whole system is simulated using MATLAB/ Simulink and the results are shown. Hardware implementation of the system in open loop is done in the laboratory with a Wind turbine Emulator and inverter setup. The inverter pulses are generated in 120 deg and 180 deg mode with variable frequency using C2000 Piccolo launchpad evaluation kit.

Keywords:Permanent Magnet synchronous Generator(PMSG), PI controller, Closed loop boost converter, Closed loop inverter , Standalone load, C2000 launch pad evaluation kit.

I. INTRODUCTION

Wind is one of the renewable sources of energy which is nonpolluting. The wind is a by-product of solar energy.
Approximately 2% of the sun's energy reaching the earth gets converted into wind energy. The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high-to low-pressure areas and also rotation of earth causes wind. This wind is capable of exerting a force and creates motion which is utilized in the wind energy conversion systems. Wind power technology is experiencing significant growth in developing countries like India. As a result of scientific assessments of wind resources throughout India, wind power has emerged as a viable and cost effective option for power generation. Also studies shows that small scale wind energy conversion systems are more efficient and cost effective. Among AC type generation systems, those based on Permanent magnet synchronous generator (PMSG) is one of the most favorable and reliable methods of power generation for small and large scale wind turbines. To meet the amplitude and frequency requirements of conventional load and grid, the amplitude and frequency outputs of PMSG require additional conditioning [1] and power electronic interfacing. Advantages of PMSGs are highest energy yield, higher active/reactive power controllability, absence of brush/slip ring, low mechanical stress, absence of copper losses on rotor, high power density, lower rotor inertia, robust construction of the rotor and low level of acoustic noise [2],[3]. Hu et al. [4] and Tan et al. [5] discusses a scheme based on a grid-connected wind turbine with a permanent magnet synchronous generator that uses a back-to-back full scale pulse width modulation (PWM) converter connected to the grid. [6] This increases the system cost and has prevented, the more widespread use of small grid-connected wind turbines. Considering the usage of permanent magnet synchronous generators, three-phase diode rectifiers followed by dc–dc choppers are more economical than three-phase insulated gate bipolar transistor (IGBT) converters. In [7], [8], a simple ac–dc–ac converter for grid-connected wind power generation systems is used with advantages that include inexpensive cost and easy control of the generator load. A wind farm with internal dc network arrangement was discussed in [9]. The dc-distribution system involves a better integration of distribution generators and the storage systems, compared with the ac-grid with respect to bi-directional power exchange and power quality [10], [11]. Whereas in [12], the protection schemes were proposed for permanent magnet synchronous generator (PMSG) wind turbines farm connected in parallel to dc-link. In variable speed wind turbine technologies, the PMSG has received increased attention because of its

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operation at high power factor, high efficiency and increased reliability due to its self excitation property [13]. Three-phase six switch rectifier is of wide interest to be used as generator side converter [14],[15] but this rectifier suffers from several disadvantages; larger power losses due to switching operation of three semiconductor devices in each interval, expensive structure, and short circuit possibility through the leg [16].This paper presents an efficient small scale wind energy conversion system using PMSG and power electronic converters. In this system the PMSG output is converted toThis constant DC output is converted to AC using a Sine PWM three phase inverter with real and reactive power control in order to satisfy the load and grid requirements. The controllers are designed through MATLAB simulation and pulses for the inverter are generated using C2000 Piccolo launchpad evaluation kit in 120 degree and 180 degree modes of conduction. The C2000 Piccolo launchpad evaluation kit is based on the F28027 microcontroller (MCU), is a modular, quick-launch evaluation kit that contains everything needed – device, emulation and software – to explore the latest digital control techniques in areas such as power, lighting and motor control. It is cost effective and simple to implement.

II. DESCRIPTION OF THE SYSTEM

A. Block diagram of the Proposed System

The wind turbine is the prime mover of the Permanent magnet synchronous generator. As the wind velocity is non uniform in nature, the output of PMSG will be fluctuating. Therefore it cannot be interfaced directly to the load. The output of PMSG is converted to DC using a full bridge rectifier and the variable DC is converted to constant DC by a closed loop Boost converter. This constant DC output is converted to AC using an inverter. This inverter is operated with Sine PWM technique with active and reactive power control and fed to the load.

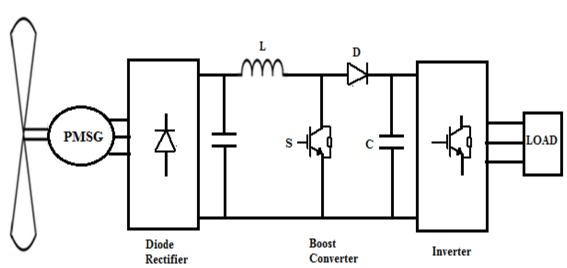

Fig. 1. Block diagram of the proposed system

B. Permanent Magnet Synchronous Generator

The Permanent magnet synchronous generators are being used in many small generating systems, particularly wind power system. The PMSG is typically constructed with magnets attached to the rotor and a three phase winding in the stator core. It is particularly an attractive option in renewable energy applications, because it has high conversion efficiency, primarily due to the fact that no energy is required to provide the magnetic field [19]. It is of simple design, robust and reliable. PMSG do not require an additional DC supply for the excitation circuit [19]. Furthermore the mechanical friction is low in comparison to other machines because there is no brush gear and does not require a gear box. These are lighter and therefore high power to weight ratio. Unlike Induction generators these do not require reactive magnetizing current for excitation. However PMSG have these advantages, the negative side is that the permanent magnets required for PMSG are quite expensive, at high temperatures the magnets get demagnetized.

C. Three phase diode rectifier

The diode rectifier is the most simple, cheap, and rugged topology used in power electronic applications. The most disadvantage of this diode rectifier is its disability to work in bi-directional power flow. The variable output dc voltage from three-phase diode bridge rectifier can be obtained.

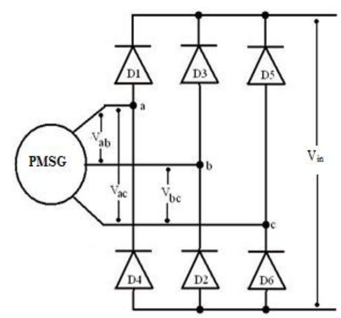

Fig. 2. Diode bridge rectifier

D. Closed Loop Boost Converter

The closed system of boost converter is obtained by using a Voltage mode PWM Scheme. The block diagram of which is shown in the figure 5.1. In this technique the output of the boost converter is kept constant by using the duty ratio as the control variable. The error amplifier compares the output voltage Vo with the reference voltage and generates the error signal. This error signal is given as the input to the PI controller. The output of the PI controller is compared with the saw-tooth signal and the pulses are generated [17],[20]. The output pulses are functions of duty cycle.

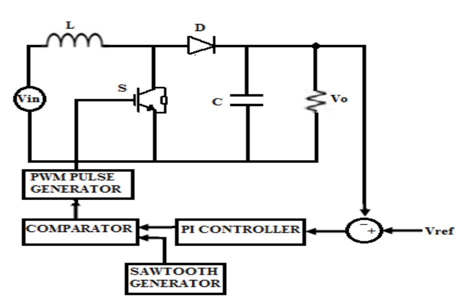

Fig. 3. Closed loop boost converter

The boost converter operate in Continuous conduction mode for $L > L_b$, where

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$$L_b = \frac{(1-d)^2 dR}{2f} \quad (2)$$

The value of the filter capacitor required is more to limit the output voltage ripple. The minimum value of filter capacitor needed is given by

$$C_{min} = \frac{dV_o}{V_r Rf} \quad (3)$$

Where d is the duty ratio
f is the switching frequency
R is the load resistor
V_r is the ripple voltage

Using the above design equations, the boost converter is designed for the proposed application with

V_{in} = 200 V; V_o = 500V; d = 0.6; f = 5kHz; R= 250Ω;
V_r = 1%;
The values of L_b obtained is
L_b = 2.4 mH; It is rounded off to 3 mH;
C_{min} = 0.48 µF; It is rounded off to 10 µF;
With these values of L, C and d, the transfer function of the boost converter is derived using state space averaging scheme. The transfer function derived is

$$\frac{X_1(s)}{U_1(s)} = \frac{13.33e^{-6}}{s^2 + 400s + 5.33e^6} \quad (4)$$

$X_1(s)$ is the s domain representation of the output voltage and $U_1(s)$ is the s domain representation of the input voltage of the boost converter.
With the derived transfer function the PI controller was designed using Ziegler Nichols tuning method [21]. In this method of tuning the step response of the system transfer function is obtained, which is a S shaped curve. On the curve the point of inflection is noted and a tangential line is drawn. The point at which this tangent touches the time axis gives the value of L, the point at which it touches the projection of the steady state value is noted and the corresponding time is noted. The difference value between this value of time and L is taken as T. The K_p and K_i values of the controller are decided using the following equations.

$$K_p = 0.9\frac{T}{L} \quad (5)$$

$$T_i = \frac{L}{0.3} \quad (6)$$

$$K_i = \frac{K_p}{T_i} \quad (7)$$

The values obtained for the given transfer function are K_p=0.0008; K_i=0.008.
An inverter is a circuit that converts DC to AC. Pulse Width Modulation (PWM) is a switching technique that is used to decrease the total harmonic distortion in the inverter circuit. The output of the boost converter is fed to a three phase inverter which converts the constant DC to constant AC having a frequency of 50 Hz. The objective in pulse-width-modulated three-phase inverters is to shape and control the three-phase output voltages in magnitude and frequency with an essentially constant input voltage V_o. To obtain balanced three-phase output voltages in a three-phase PWM inverter, the triangular voltage waveform is compared with three sinusoidal control voltages that are 120 deg out of phase. The schematic diagram of a three phase inverter is shown in the figure.

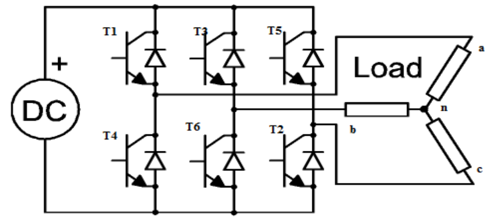

Fig. 4 Schematic diagram of three phase inverter

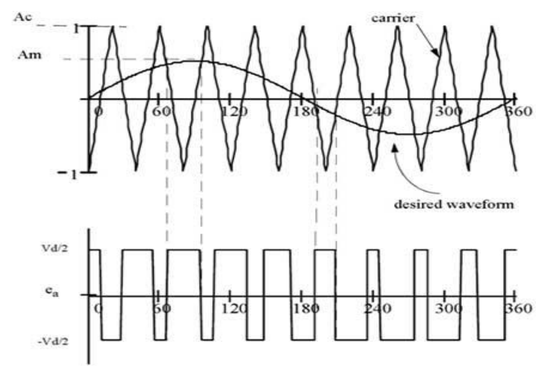

Fig. 5. Sine PWM technique for one phase

There are six switches which are operated in a sequence based on the pulses generated by Sine PWM technique The switches are operated in 120 degree conduction mode. In this mode each transistor conducts for 120deg. Only two transistors remain ON at any instant of time. The output of the three phase inverter is given to the R load. For realizing Sine PWM, a high frequency carrier wave is compared with a sinusoidal reference wave of desired frequency. The intersection of the two waves determines the switching instants and commutation of the modulated pulse. A_c is the peak value of the triangular carrier wave and A_r is the peak value of the modulating signal. The carrier and the reference waves are mixed in a comparator. When the sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise it is low. The comparator output is processed in such a manner that the output voltage wave of the inverter has a pulse width agreement with the comparator output pulse width.The diagram shows the power circuit diagram of a three phase inverter. There are two possible patterns of gating the thyristors. In one pattern each thyristor conducts for 180deg and in other each conducts for 120deg.But in both these patterns gating signals are applied and removed at 60deg intervals of the output voltage waveforms.

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E. Closed Loop Boost Converter

For obtaining a closed loop control of three phase inverter the reference wave for the sine PWM technique is generated through the PI controllers. Two controllers are used one is for d component control anther is for q component control. The dqo components are then converted to abc frame to get the three reference waveforms which are then compared with the carrier wave and the required pulses are generated.

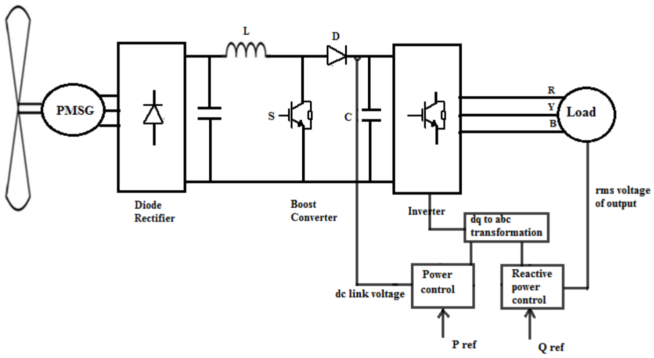

Fig. 6. Closed loop inverter block diagram

III. SIMULATION RESULTS

The simulink model of the proposed work is given in figure 7. This model has three subsystems namely Wind turbine and diode rectifier, closed loop boost converter and a closed loop three phase inverter fed to a RL load.

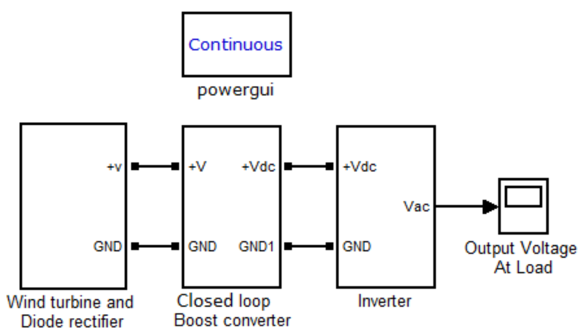

Fig. 7. Simulink model of the proposed system

The simulink model of the wind turbine and the diode rectifier is shown in figure 8. The PMSG used has a rating of 300V, 4500 rpm, 6Nm. The 3 phase ac from the PMSG is rectified using a three diode rectifier bridge. The output obtained is an uncontrolled dc which is regulated to a constant dc in the boost converter.

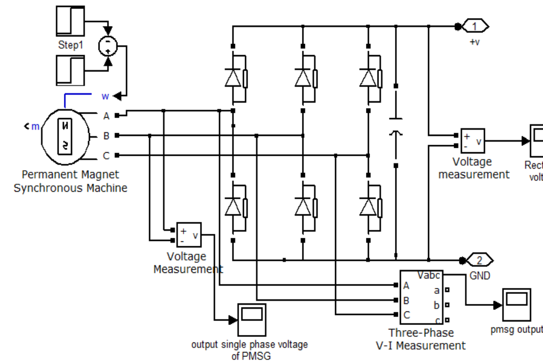

Fig. 8. Simulink model of PMSG fed Diode Rectifier

The figure 9 gives the simulink model of a closed loop boost converter. In this model the output voltage is sensed and compared with the reference voltage of 500V. The error signal is given as the input to the PI controller whose Kp and Ki values are 0.0008, 0.008 respectively. The signal from the PI controller is compared with the saw tooth waveform and the pulse for switching is generated whenever the error signal is greater than the saw tooth signal. The output pulse is a function of duty cycle and is given to the switch.

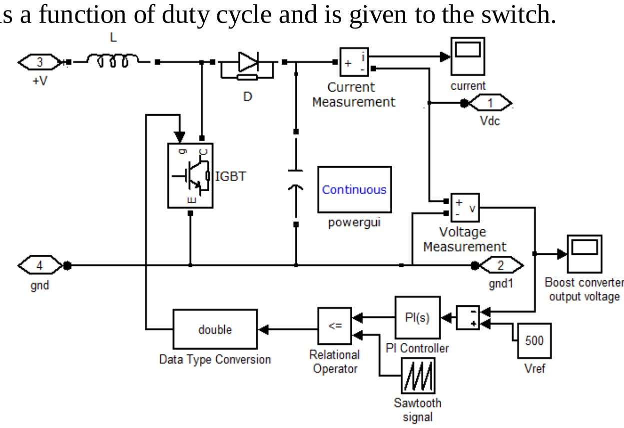

Fig. 9. Simulink model of closed loop boost converter

The figure 10 gives the simulink model of the closed loop inverter feeding a standalone RL load. The inverter used is a three phase bridge inverter which uses IGBT as the switch. The pulses for the switches are obtained by comparing a reference wave and a triangular carrier wave. In this system the reference wave is generated from the PI controller. The dc link voltage is compared with reference and given to the PI controller. The controller output results in the d component. The RMS value of the grid voltage is compared with its reference and given to a PI controller. The output of the controller gives the q component. The resulting dqo components are converted to abc reference frame to get the reference wave. The values of proportional and integral gains for the d controller are Kp=0.0049, Ki=0.00745. The values of proportional and integral gains for q controller are Kp=0.13, Ki=1.7. with these values the reference voltage is obtained.

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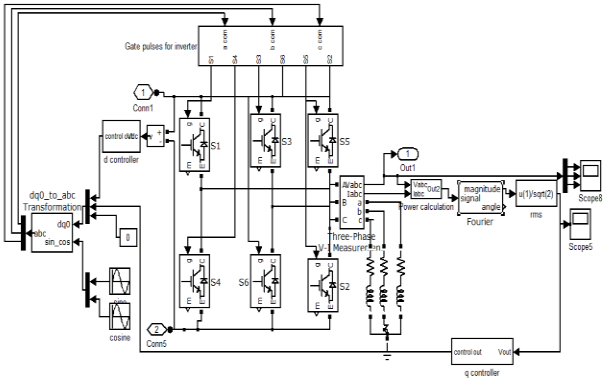

Fig.10. Simulink model of closed loop inverter

The figure 11shows that the dc link voltage at the output of boost converter is maintained constant at 500 V. The figure 12 shows the output voltage at the load. The figure 13 shows the rms value of output voltage at the load.

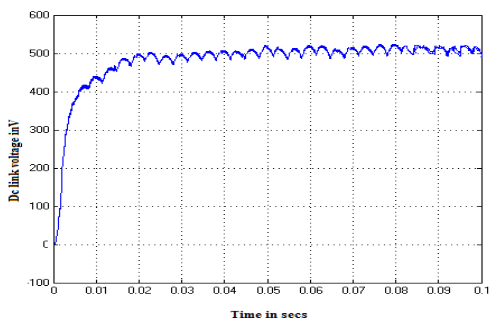

Fig. 11. Output voltage of boost converter

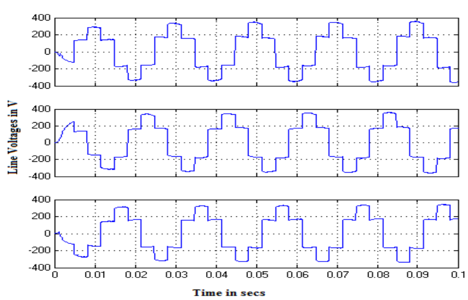

Fig. 12. Output voltage at the load

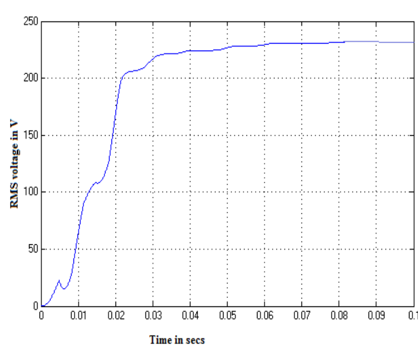

Fig. 13. Output RMS voltage at the load

IV. HARDWARE IMPLEMENTATION

The system is implemented in open loop and the necessary pulses are generated using C2000 Piccolo launchpad evaluation kit based on the F28027 microcontroller. The basic hardware block diagram of a standalone scheme is shown in the figure 14. The major blocks of the system are

i) Wind Turbine emulator
ii) PMSG
iii) Diode bridge rectifier with inverter
iv) C2000 Piccolo launchpad
v) Level shifter
vi) Load

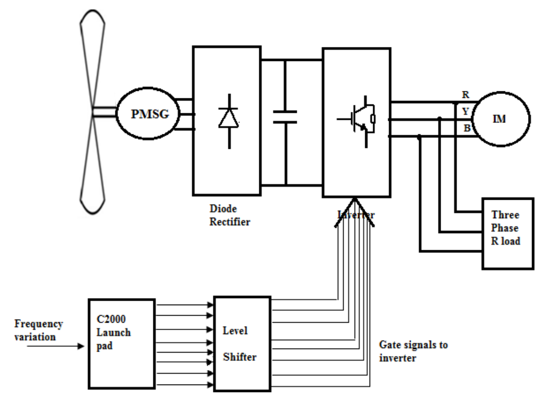

Fig. 14. Hardware block diagram of the proposed system

For the laboratory purpose the wind turbine is emulated using a induction motor and gear set up with speed control. The emulator used in the project is a VFD controlled 3 phase,50 Hz, 5HP,415V, 1430 rpm induction motor which is coupled with the PMSG through a gear box, which reduces the speed of the induction motor so that it emulates the behaviour of wind turbine. In this gear box the speed is reduced five times. Variations in speed of the wind can be obtained by varying the speed of the induction motor in the VFD panel.

The Permanent magnet synchronous generator used in the project is a three phase, 50 Hz, 1 KW, 200rpm, 400V and 1.4 A machine. This output is enough to drive a 0.5 HP induction motor so boost converter is not used in implementation. The output from the PMSG is connected to the diode rectifier and inverter. The output from the PMSG is given to the diode rectifier and inverter circuit. The three phase diode bridge rectifier, dc link capacitor and inverter circuit consisting of six IGBTs is built in a kit. The gate pulses for the inverter circuit can be given externally from the C2000 Piccolo launchpad.

The C2000 Piccolo launchpad evaluation kit, based on the F28027 microcontroller(MCU),is a modular quick launch evaluation kit that contains every thing needed- device, emulation and software- to explore the latest digital control techniques in areas such as power, lighting and motor control. Its part number is LAUNCHXL-F28027. There are various prototype features namely

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i) On board JTAG emulator eliminates need for external emulator
ii) Double sided header pins for easy access to peripheral pins and C2000 booster pack expansions.
iii) No external hardware required to get started on C2000 launhpad.

Peripheral features:
i) It has a 32 bit CPU.
ii) High speed of operation with CPU speed of 60 MHz, which can be reduced by programming if required.
iii) It has high memory with 12KB RAM and 64 KB Flash memories.
iv) It has 8 PWM channels and 4 HRPWM channels.
v) 9 timers, and 1 capture unit.
vi) It has 1 12 bit ADC with speed of 4600KBPS
vii) It has facilities for connecting SPI, SCI/UART, and I^2C modules

The Enhanced PWM module, Interrupts and ADC modules are used in the project to generate the necessary pulses for the Inverter. The EPWM module consists of various sub modules namely

- Time base module
- Counter compare module
- Action qualifier module
- Dead band Generator module
- PWM Chopper module
- Trip zone module
- Event trigger module

Each ePWM module supports a dedicated time base counter with period and frequency control. This time base register is to be configured to get the required tme period and frequency of the pulse. It can generate two PWM outputs EPWMA and EPWMB.It ahs programmable phase control support for lag or lead operation relative to other ePWM modules, which can be used for producing the required phase shift between pulses. All events can trigger both CPU interrupts and ADC start of conversion. The PWM outputs can be made available in the external GPIO pins. There are various registers such as Time period register, Counter compare register, Action qualifier register, Dead band register which needs to be configured properly to get the required pulses in both 120deg and 180deg mode of operation. The ADC is 12 bit and is used to change the frequency of the pulses. The maximum magnitude of the pulse that can be obtained from the processor is only 3.3 V. This low voltage cannot drive the gate of the IGBT and also the default state of the output is high which may make the switches in the same arm of the inverter to be turned on simultaneously. Because of the reasons a level shifter circuit is used to rise the level of the pulses to 15V and inverted.

The load used in the implementation is a induction motor along with a three phase R load. The R load is a 1 KW rheostat and induction motor is a 3 phase, 50Hz, 415V, 0.5HP, 1A and 1440rpm motor.

The block shown was implemented and the following results were obtained. The wind emulator was run in various speeds and the gate pulses to the inverter were given at various frequencies in 120deg mode and 180 deg mode of conduction and the results were obtained as follows. The line to line voltages at the inverter in 180 deg and 120 deg are shown in the figures15 1nd 16 respectively.

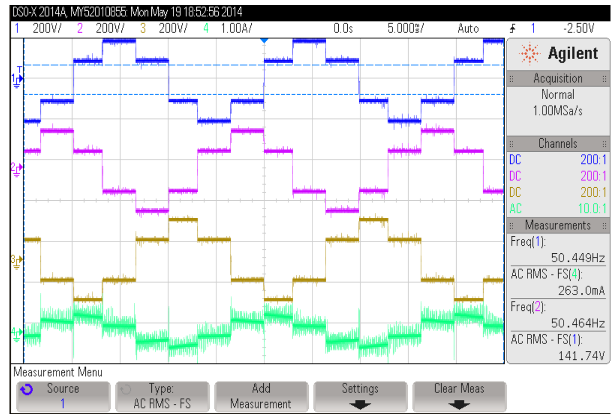

Fig. 15. Line to line voltage at the inverter in 180deg mode when the system is connected to 3 phase induction machine

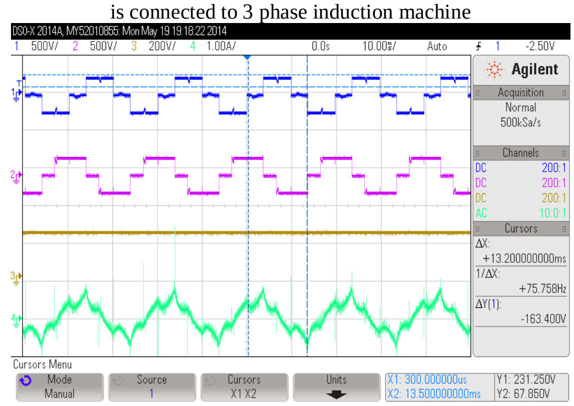

Fig. 16. Line to line voltage at the inverter in 120deg mode when the system is connected to 3 phase induction machine

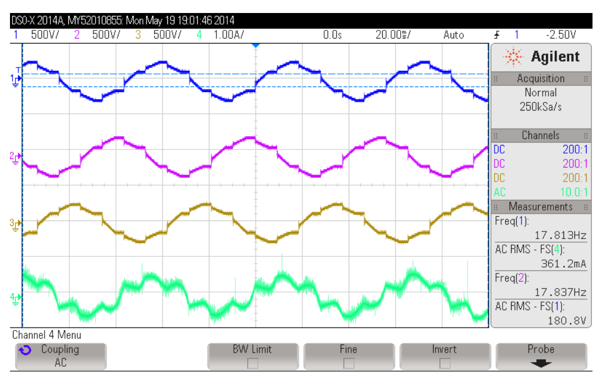

Fig. 17. PMSG output voltage and current

The photograph of the hardware setup showing the C2000 launchpad kit, Diode rectifier and load is shown in figure taken at the laboratory is shown in the figure 18.

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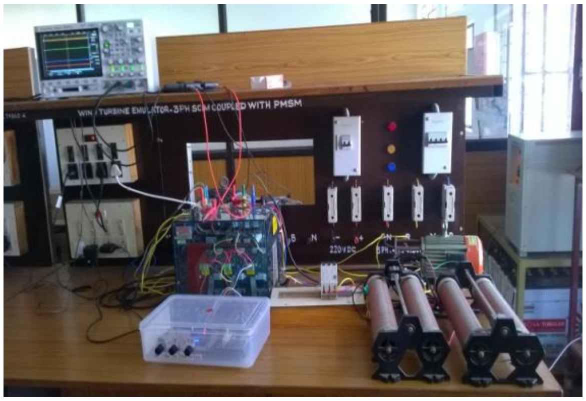

Fig. 18. Hardware setup showing the c2000 launchpad kit, Diode rectifier and load.

The photograph of hardware setup showing the wind turbine emulator and PMSG is shown in the figure 19.

Fig. 19. Hardware setup showing the Wind turbine Emulator and PMSG.

V. CONCLUSION

In this work, the power electronic topology for variable wind energy conversion system based on Permanent magnet synchronous generator (PMSG) is presented. The controller design for the same scheme in standalone mode is presented. The stability and design of closed loop dc-dc converter is presented. The wind driven PMSG is connected to an RL load through a ac- dc- ac power converter. In order to connect the system to grid the magnitude and frequency of the output should be synchronized with the grid and should be compatible to variations in the generator speed. The magnitude can be maintained constant with a closed loop boost converter and the frequency can be controlled with an inverter control even with variations in generator speed. The boost converter in the proposed system was designed and modelled using state space averaging scheme. A closed loop PI controller is designed for the boost converter using Ziegler Nichol's technique, in order to maintain the dc link voltage for the inverter a constant. The inverter is used in closed loop for the generation of the sine PWM technique. The scheme is first simulated in standalone mode with RL load . In this scheme the output voltage, real power and reactive power are controlled using PI controller. The entire scheme is simulated in MATLAB/SIMULINK platform. Various simulations are carried out for wind speed variation and load variation. The adaptability of the proposed controller for these disturbances and range of speed and load variations that the controller works is presented. It is observed that the dc link voltage is maintained constant for the variation of PMSG speed between ±30% of the rated speed with a steady state error of ±10%.

Hardware for the proposed scheme is done for standalone mode in open loop with both three phase R load and induction motor. The pulses for the boost converter and inverter are generated using C2000 Piccolo launchpad in 120 degree 180degree mode of conduction.

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