Wind Energy Conversion System

Senior Project Report

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ABSTRACT

The purpose of this project is to design and implement a Wind Energy Conversion System (WECS). This system consists of a three-phase generator, followed by a three-phase diode rectifier, connected to a boost converter, and finally a single phase inverter system. The boost converter and inverter controllers are realized with a Texas Instruments 32-bit fixed point TMS320F2812 Digital Signal Processor (DSP) board. The output voltage of the boost converter is maintained constantly by adjusting the duty ratio throughout a voltage-current controllers. The inverter is controlled by a Sinusoidal Pulse Width Modulation (SPWM) technique. The proposed design of this wind energy conversion system is simulated in PSIM, a power electronics simulation program and verified on a 1kW small scale DSP-controlled system.

INTRODUCTION

With the increasing demand for renewable energy sources, wind power generation has become a popular option for electricity power generation, which is both environmentally friendly and economically competitive. A wind energy conversion system basically is a system that converts kinetic energy of the wind into electricity without any excess pollutants. A typical wind energy conversion system consists of a wind turbine, a generator, power electronics interface, and control systems. The primary focus of this project is to design and implement the power electronics interface and control systems of a wind energy conversion system in a small scale model of 1kW.

PROJECT SUMMARY

The purpose of this project is to design and implement a wind system conversion system that interfaces a wind turbine with a single phase utility line. This system consists of a brushless DC motor, a three phase diode rectifier, a boost converter, and a grid tie single phase inverter. The boost converter and inverter are controlled by a TMS 320 F2812 Digital Signal Processor. The boost converter is controlled by a voltage-current controllers, which maintain the output voltage of the boost converter at a constant, and the inverter is controlled by a unipolar pulse width modulation technique, one of SPWM techniques in order to output a sinusoidal voltage 120 $V_{rms,}$ AC at 60 Hz despite fluctuating wind conditions.

OVERALL SYSTEM DIAGRAM

This system, as shown in Figure 1and 2, uses an induction motor to simulate the rotation of a wind turbine, which is coupled with the brushless DC motor. This induction motor is powerful enough to turn the shaft of the brushless DC motor in order to emulate a wind turbine system. The three phase diode rectifier will convert the variableng frequency and magnitude 3 phase-sinusoidal voltages produced by the brushless DC motor which acts as a generator into a smooth DC voltage. Then the DSP-controlled boost converter will increase DC voltage up to 200 V such that the inverter can convert the DC voltage to 120 V_{rms} , AC. The converted AC could be connected to the grid. An overall circuit of the power converters is shown below in Figure 2. Each subsystem is discussed in greater detail in the following section.

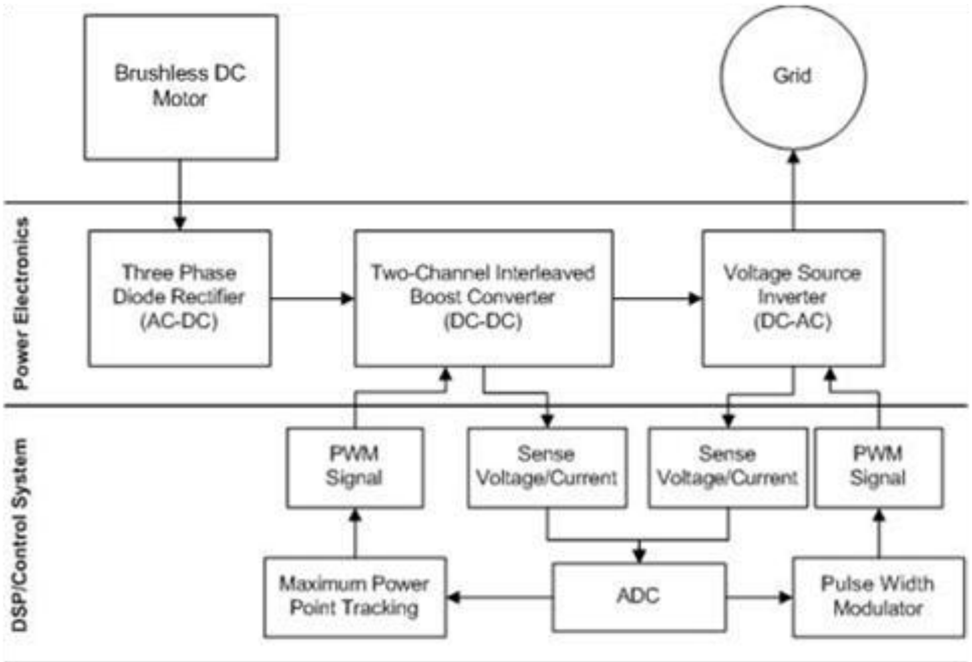

Figure 1 Top Level System Diagram

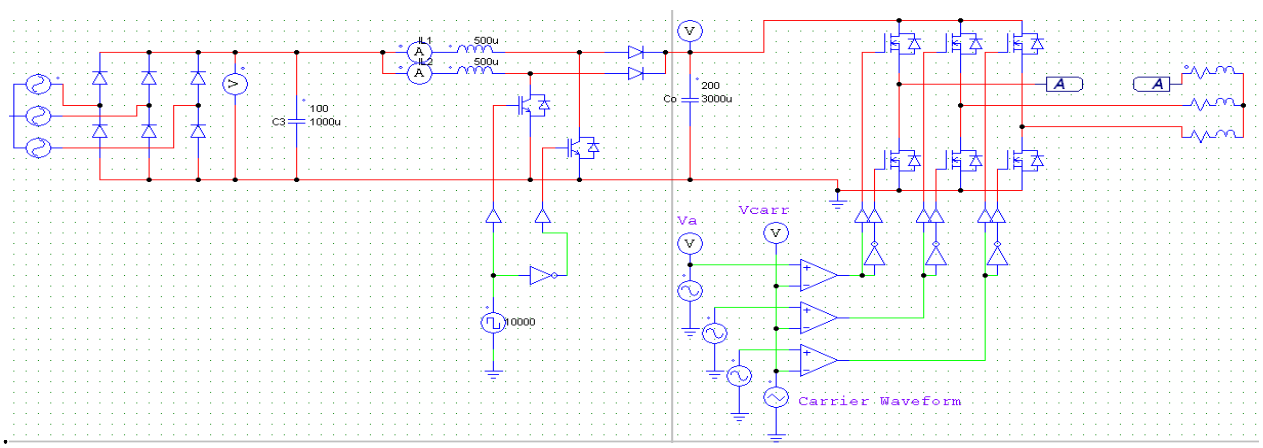

Figure 2 Overall System Circuit

SUBSYSTEM DESCRIPTION

BRUSHLESS DC MOTOR

The purpose of the brushless DC(BLDC) motor is to convert mechanical energy created from wind into electrical energy. When this BLDC motor is rotating, its 3 phase- trapezoidal waveforms can be used as a generator 3-phase AC ouput. In the case of using Permant Magent Sychronous Generator, a pure 3-phase sinusoidal waveforms can be achieved.

THREE-PHASE DIODE RECTIFIER

The three-phase diode rectifier converts the variable AC voltage from the generator to DC voltage. As seen in Figure 2, the circuit consists of 6 diodes, a top group of 3 diodes and a bottom group of 3 diodes . At least one diode of each group must conduct during the operation such that the current from the generator to the boost converter flows continously. To faciliate the flow of the current, in the top group, all diodes have their cathodes connected together and in the bottom group, all diodes have their anodes connected together[1,2].

BOOST CONVERTER

The boost converter is a DC-DC converter driven by a PWM signal generated from the DSP. The main purpose of the boost converter is to increase the variable DC voltage from the diode rectifier to a constant voltage which is fed into the single-phase inverter. The circuit of the boost converter is shown in Figure 3. The input of the boost converter is the variable rectified sinusoidal voltage and the output is a constant voltage, which is transferred to the inverter.

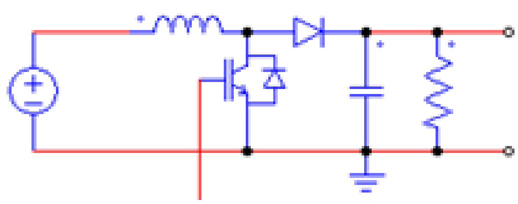

Figure3 Boost Converter Circuit

The boost converter works by storing enough energy in the inductor so that the output is the desired voltage throughout the switching action. When the switch is closed, the energy is stored in the inductor. Then the energy is transferred to the capacitor when the switch is open. The switch is controlled by a PWM signal. The duty cycle of the PWM signal determines the output voltage, as described in the following relationship[1,2]:

$$V_o = \frac{V_i}{1-D} \quad (1)$$

Where V_i is the input voltage, V_o is the output voltage and D is the duty ratio. For example, the output voltage is twice the input voltage when the duty ratio of the PWM signal is 50%.

The switching scheme is controlled by a proportional-integrator (PI) controller which determines the duty cycle so that the output voltage is constant regardless of the input voltage. A voltage-current PI controllers were implemented in SIMULINK.

The purpose of this voltage-current controller is to determine the duty cycle ratio based on the errors of the actual and reference voltage and current. As shown in Figure 4, the controller measures the inductor current and the output voltage through the Analog to Digital Coversion block on the DSP board. The DSP board converts the voltage and current values into a hex value, so a data conversion is used to in order to convert it to double and is scaled as the necessary actual value[6]. Then it goes through a digital filter to remove noise from the incoming signals. Then it goes through a cascade type of PI controllers: the first one is mainly related to the voltage controller and and the other is to control the inductor current of the boost convertert. The calculations of k_p and k_i gains are discussed in a later section. The DSP outputs as a PWM signal with determined duty ratio in order to output the desired voltage. Using this voltage controller , we can maintain a constant output voltage.

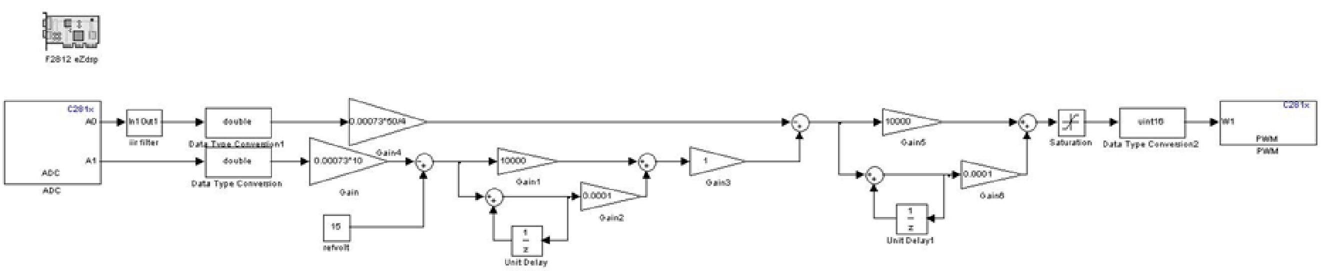

Figure 4Voltage and current controllers

Also, an interleaved boost converter was considered for this project to reduce the ripple effect of the boost converter. The two-channel interleaved boost converter has an extra set of inductor and diode in parallel as shown in Figure 5[5].

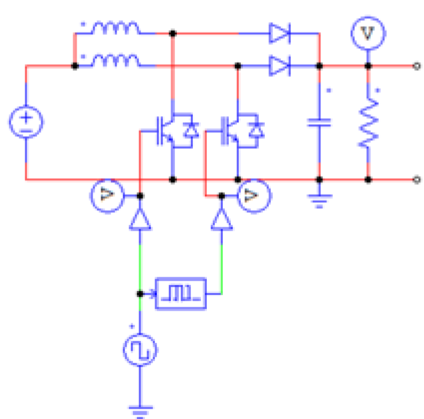

Figure 5 PSIM two-channel interleaved boost converter

This topology allows the input current to be spilt between the two channels as shown in Figure 6 . In addition, this boost converter topology improves the power factor and decreases the total harmonics distortion, improve the power factor, decrease the total harmonic distortion, and minimize the current and voltage ripples.

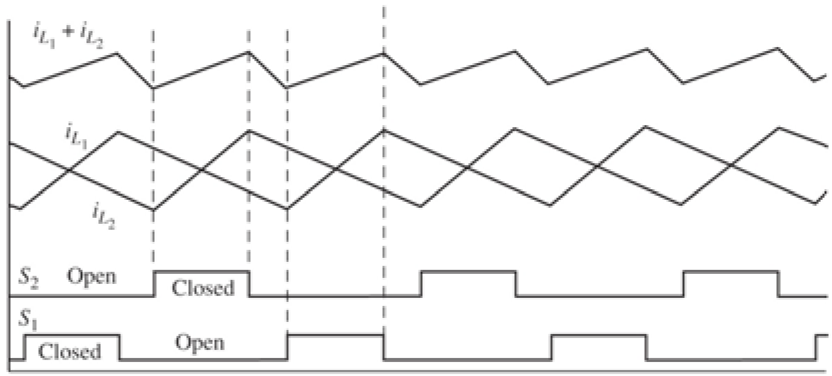

Figure 6 input current between two channels[5]

SINGLEPHASE INVERTER

The final subsystem in our project converter system is to use DC-AC inverter system such that it can be fed into the grid. For this project, a single-phase voltage inverter was implemented. The topology of this single phase inverter is a full-bridge circuit followed by a LC filter and then a line frequency transformer as shown in Figure 7.

A switching algorithm was implemented on TMS320 F2812 DSP board in order to switch the IGBTs so that the inverter generates a sinusoidal voltage with the desired amplitude and frequency. In this project, the inverter will be controlled by the unipolar PWM technique to output of voltage of 120 V_{rms} AC at 60 Hz. The unipolar PWM algorithm is discussed in the following section.

The output of the full-bridge circuit with the unipolar PWM switching scheme is a PWM signal, so a LC filter transforms it to a sinusoidal output. The value of the inductor and capacitor is discussed in a later section.

The transformer is essential for this DC-AC converter topology for galvanic isolation purposes. A line frequency transformer helps to isolate the power converter system from the grid as a safety precaution and for functional operation regardless of ground leakage current.

UNIPOLAR PULSE WIDTH MODULATION

There are two sinusoidal pulse width modulation (SPWM) techniques in the literature such as bipolar PWM and unipolar PWM. A common switching technique for an inverter with the aforementioned topology is unipolar PWM.

This single-phase inverter system in Figure 7 will be controlled by the unipolar PWM technique. This topology with unipolar PWM is advantageous over the bipolar technique since the maximum current ripple is smaller than the maximum current ripple when using bipolar PWM technique[1,2]. In general, a sinusoidal pulse width modulation scheme compares a sinusoidal waveform of desired output frequency and amplitude with a triangle waveform. The frequency of the triangle waveform is the switching frequency of the four IGBTs in the inverter circuit. The comparison of the sinusoidal waveform and the triangle waveform generates a PWM waveform such that when the sinusoidal waveform value is greater than triangle waveform value, the PWM output is high, and otherwise, the PWM output is low.

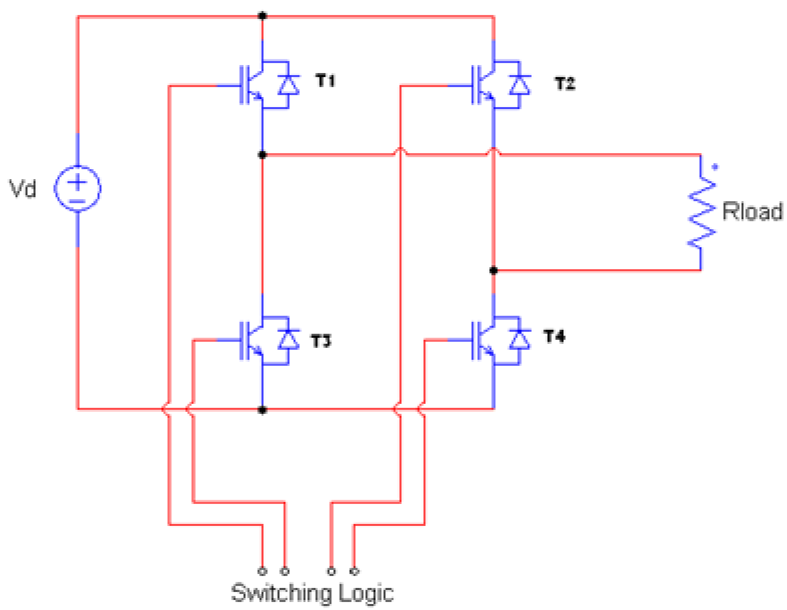

Figure 7 Single phase inverter

In the unipolar PWM technique, voltage output of fullbridge circuit is either positive, zero, or negative. The legs of the full-bridge circuit are controlled independently in this technique. Two transitional PWM outputs are generated, in which one of the signal is out of phase by 180 degrees, so that each leg is controlled independently. In order to generate the second transitional PWM output, the triangle waveform is compared to a sinusoidal waveform which is out of phase by 180 degrees. This will control the IGBTs so that the inverter outputs the following switching scheme:

$$V_{out} = V_d \qquad \text{If T1,T4 is on}$$
$$V_{out} = -V_d \qquad \text{If T2,T3 is on} \qquad (2)$$
$$V_{out} = 0 \qquad \text{Otherwise.}$$

The desired PWM signals are shown in Figure 8 .

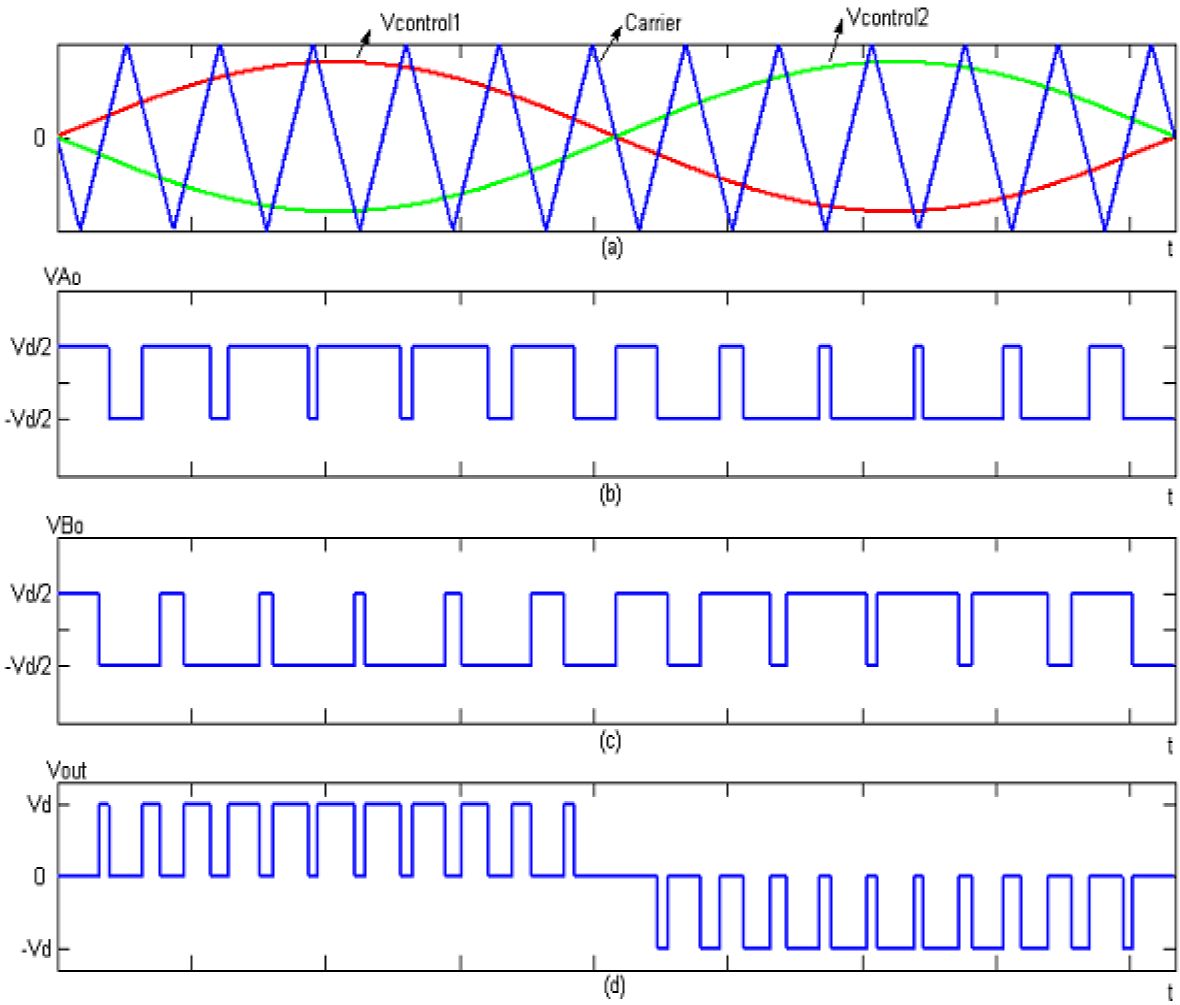

Figure 8 Desired PWM signals

This algorithm was modeled in Simulink as shown in Figure 9.

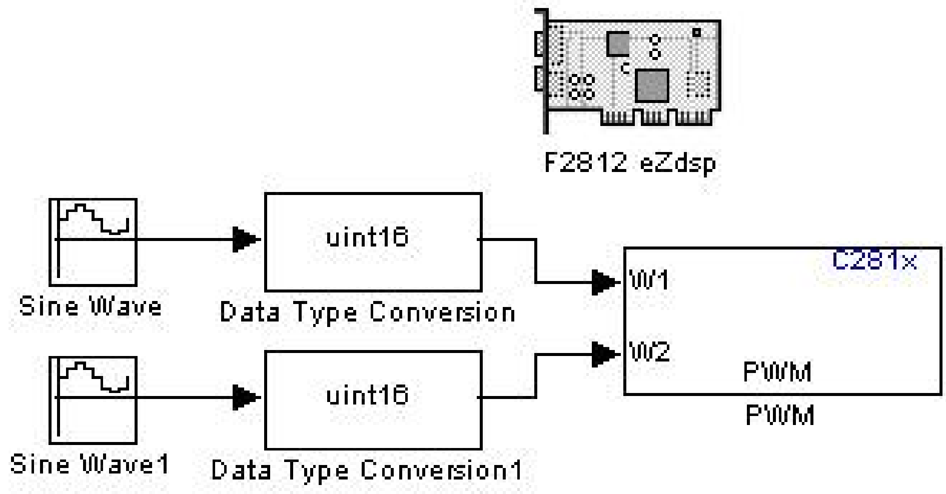

Figure 9 Simulink algorithm

POWER SUPPLY (SINGLE-PHASE DIODE RECTIFIER)

To power the gates of the IGBTs, which are used in the interleaved boost converter and inverter, a power supply was designed to create a 15V and 5V supply. The 15V was used to supply power to switch the gates of the IGBTs and the 5V supply was used to power the gate driver IC that would drive 15V signal to the gates of the IGBT's. Using a 8.4:1 transformer which takes the peak to peak AC voltage down by a factor of 8.4, the voltage was easily converted to DC with a singlephase diode rectifier. The singlephase rectifier converts all negative voltages from the AC voltage into positive voltages. With the use of a capacitor the absolute sinusoidal signal was smoothed to flat DC using a capacitor. The 15V and 5V values were ensured by voltage regulators.

DIGITAL SIGNAL PROCESSING BOARD

The boost converter and inverter controllers were implemented on the controllers on the Spectrum Digital eZdsp F2812 DSP board in Figure 10. This DSP board is based on a 32-bit DSP, can deliver up to 150 MIPS, contains 16 ultra-fast ADCs, and output 16 PWM signals. Simulink was used to construct the controllers and automatically generate the corresponding C code. Then the C code was downloaded onto the eZdsp F2812 DSP board using Code Composer. In addition, voltage and current sensing circuits were needed in order to limit the current and voltage to an acceptable range for the ADC input.

Figure 10 DSP board image

The main purpose of the voltage and current sensing circuit is to step down the output voltage of the boost converter to between 0 V and 3.3 V and isolate the DSP control system from the power converter. The current is measured by a current transducer. The voltage divider circuit lowers the voltage to the desired voltage range. The op amp protects the DSP from the high current generated by the boost converter, and the two diodes aid to protect the DSP from voltages over 3.3 V.

PARTS

- Brushless DC Motor
  - BLZ363S-160V-3000-750
- Three-Phase Diode
  - Vishay VS-26MT60
- Boost Converter
  - Diode: HFA50PA60C
  - IGBT: Fairchild HGTG30N60A4
  - Inductor: Wurth Electronics 7448263505
  - Capacitor: 5000 uF
- Inverter
  - IGBT: Fairchild HGTG30N60A4
  - Capacitor: 470 uF

    - Inductor: Wurth Electronics 7448263505
    - Various Power Resistors
- Power Supply (Single Phase Diode Rectifier)
    - Transformer: Tamura 3FL12-475
    - AC wall-outlet adapter
    - Fuse
    - Capacitor: 470uF
    - Diode: 1033
- Gate Driver
    - IR2110
    - Capacitor: .1 uF
    - Diode: 1033
    - 15V Regulator: LM7815
    - 5V Regulator: LM8L05
- Digital Controller
    - Spectrum Digital eZdsp F2812 for TI TMS320F2812 DSP
    - Code Composer Studio 3.1
    - Mathworks Matlab & Simulink 2008
- Voltage Sensor
    - Op Amp: OP484FPZ
    - 3.3 V Regulator: LM1117
    - Various Power Resistors
    - Diode: 1033
- Current Senor
    - Current Transducer: L08P050D15
    - Diode: 1033

- Op Amp: OP484FPZ
- Various Power Resistors

CALCULATIONS

Rectifier Capacitor Filter

<u>Variables</u>

Max Input Current: 5.4A

Max Input Voltage: 160V

<u>Equations Used</u>

V = I*R

V_o=(1.35V_{in} – V_{Diode}), where V_{in} is three-phase voltage, V_{Diode} is the diode drop voltage, and V_o is DC voltage

P = I*V

N_r=(120*f)/(poles), where f is frequency, poles is number of poles of motor, and N_r is RPM of rotor.

C=(V_P/2*F*V_R), where V_P is peak voltage, F is frequency, V_R is voltage ripple, and C is capacitor value.

<u>Values Used:</u>

Vin = 64.0 V

Vo = 84.0 V

Io = 961 mA

Speed = 3000 RPM

R = 88Ω

P = 80.72W

C = 534uF

Boost Converter

Equations Used:

Vo=Vin/(1-D)

LC FILTER

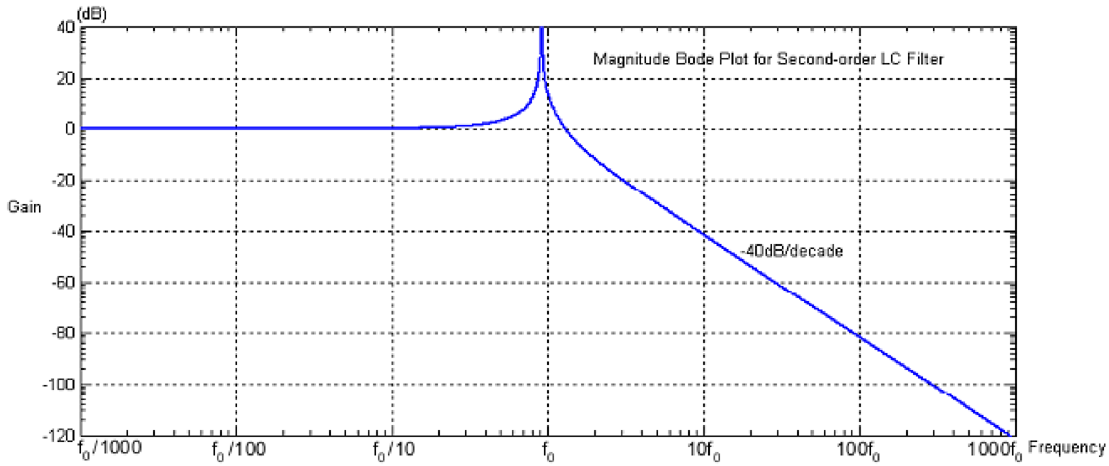

Figure 11 Magnitude Bode Plot for Second Order LC Filter

$$G(s) = \frac{1}{s^2 \cdot L \cdot C + 1}$$ **(3)**

$$C = \frac{1 - |G(s)|}{|G(s)| \cdot \omega^2 \cdot L} = \frac{1 - |G(s)|}{|G(s)| \cdot (2\pi f)^2 \cdot L}$$ **(4)**

Using the bode plot of Figure 11, we chose L = .125mH and the equation yields C = 240uF

PI CONTROLLER GAINS

To determine the Ki and Kp gains for the PI controller, we examined the magnitude and phase bode plots of the small signal model and used the following three relationships to determine the Ki and Kp[2]:

$$G_{ps}(s) \cdot G_i(s) = 1$$ (5)

$$G_{ps}(s) = \frac{\tilde{i}_L(s)}{\tilde{d}(s)}(s) = \frac{V_o}{sL_d} \quad (6)$$

$$G_i(s) = \frac{k_p s + k_i}{s} \quad (7)$$

The magnitude and phase bode plots were generated using the following MATLAB code:

```
figure(1)
%f = linspace(30,30e3,500);         % generate frequency points to be evaluated
f = logspace(1,4,500);              % generate frequency points in log scale
w = 2*pi*f;                         % 'freqs' needs frequency in radians/sec
H = freqs(num, den, w)  % to obtain frequency responses: amplitude and phase
amp = abs(H);           % amp in linear scale
phase = angle(H)*180/pi;

magdB = 20*log10(amp);  % magdB is the amplitude frequency response in decibel.

figure(1), subplot(211), semilogx(f, magdB(1,:)), title('amplitude response in dB'),grid
subplot(212),semilogx(f, phase(1,:)), title('phase response in degree')

grid, xlabel('frequency in Hz'),ylabel('degree')
```

SIMULATIONS

THREE-PHASE RECTIFIER

Figure 12 shows the three-phase diode rectifier circuit with the input and capacitor.

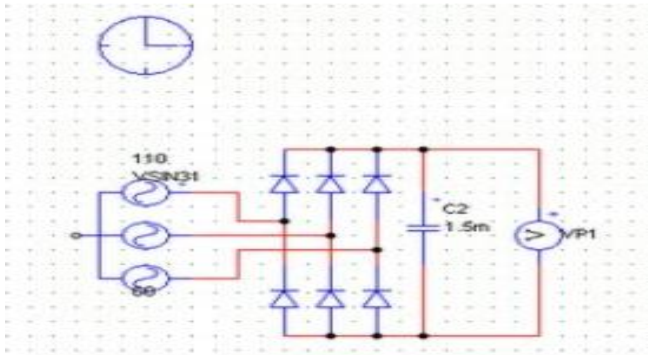

Figure 12 Three-phase diode rectifier with capacitor

In the table 1, we can compare the simulated output voltages with the theoretical output voltages based upon the input voltage variations.

Table 1 Rectifier Values

VinRMS	Vout Simulation	Vout Theoretical	Percent Error
10	14.1	13.2	4.44%
20	28.5	27	5.56%
40	56.5	54	463%
60	84.5	81	4.32%
80	113	108	4.63%
100	140.5	135	4.07%
120	169.5	162	4.63%

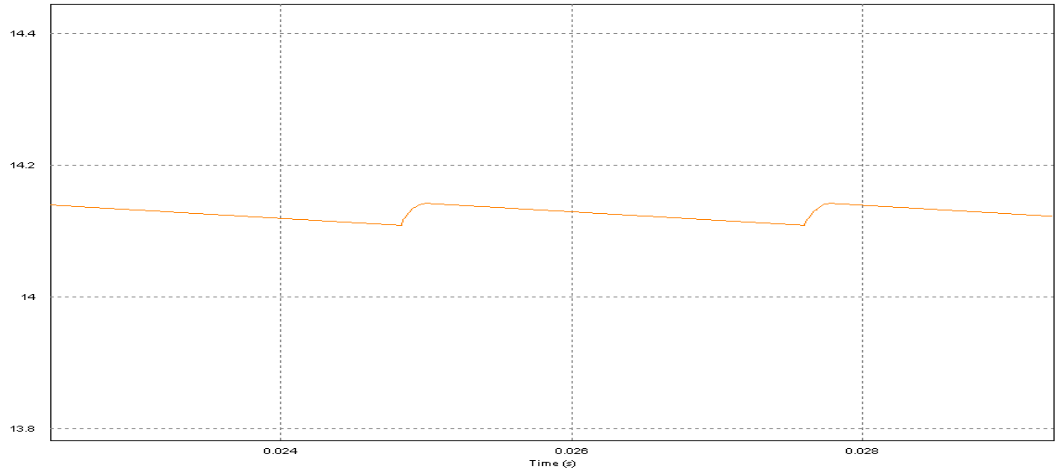

Figure 13 Three-phase diode rectifier output with capacitor

The three-phase diode rectifier was simulated using PSIM. The circuit is modeled in PSIM as shown in Figure 12. The theoretical voltage output form a three phase diode rectifier is found by Vout=1.35Vin-rms. The Table above shows the results from the PSIM simulation and the theoretical voltage. Figure 13 illustrates the DC voltage output of the diode rectifier with added capacitor.

SINGLE BOOST CONVERTER (OPEN-LOOP)

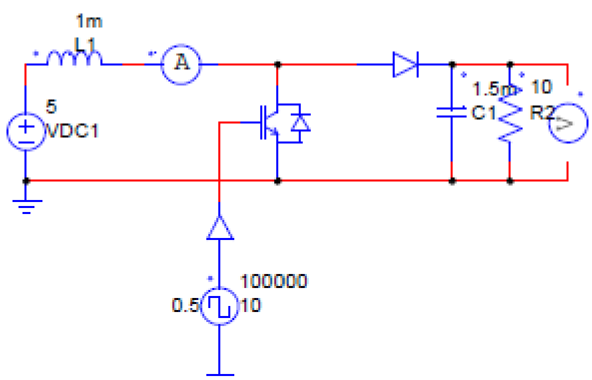

Figure 14 Boost Converter Circuit

Figure 14 show the boost converter circuit with 50% duty ratio and 10kHz switching frequency.

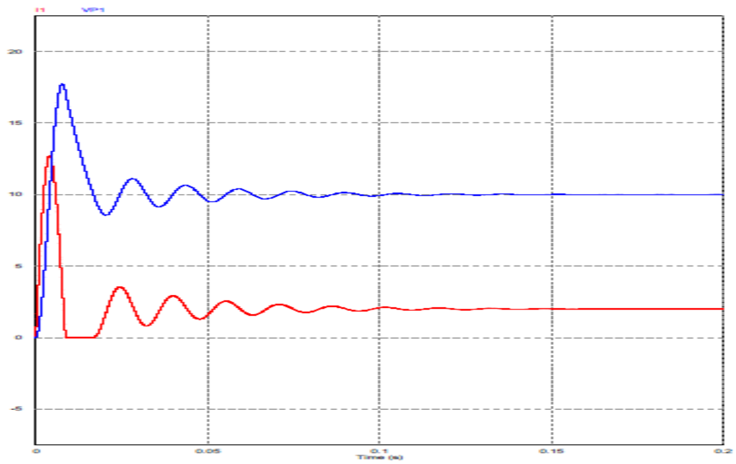

Figure 15 Boost Converter Output

Figure 15 shows the output voltage in the top and the inductor current in the bottom of the boost converter.

TWO CHANNEL BOOST CONVERTER (OPEN-LOOP)

Figure 16 shows the two channel interleaved boost converter circuit with 50% duty ratio and 10kHz switching frequency. Each switching signal is out of phase by 180 degree.

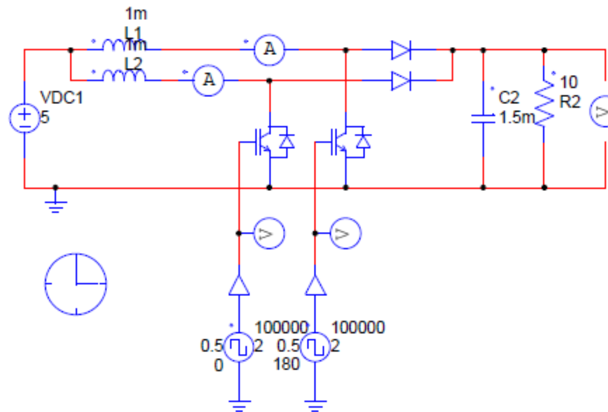

Figure 16Two Channel Interleaved Boost Converter Circuit

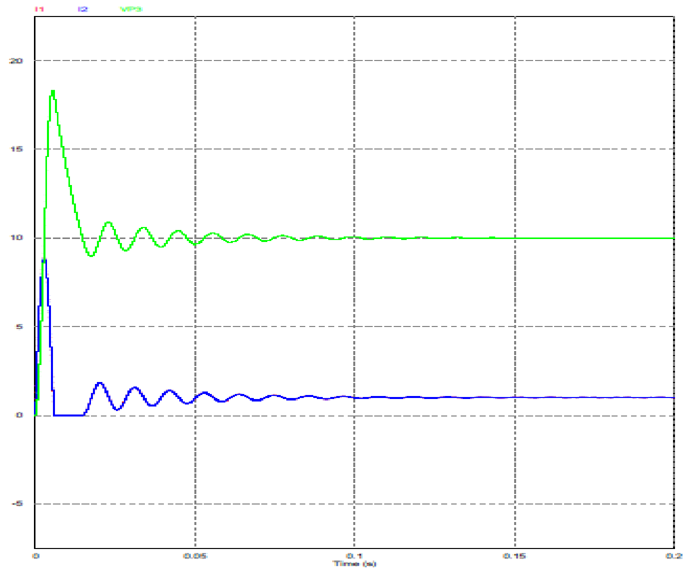

Figure 17 Two Channel Boost Converter Output

In Figure 17,the output voltage in the top and the inductor current in the bottom of the two channel interleaved boost converter can be observed .

In the table 1, we can compare the simulated output voltages with the theoretically calculated output voltages based upon the duty cycle variations.

Table 2 Values of Two Channel Boost Converter

V input	Duty-Cycle	Vo calculation	Vo simulation	% Error
5	20%	6.25	6.3	0.8%
5	40%	8.33	8.3	0.6%
5	60%	12.5	12.5	0.0%
5	80%	25	25	0.0%

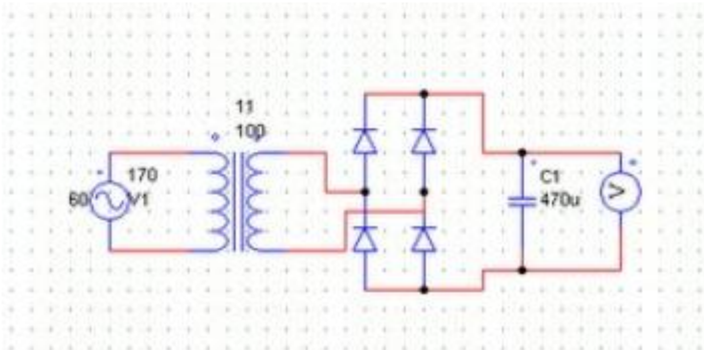

Figure 18 Rectifier with capacitor

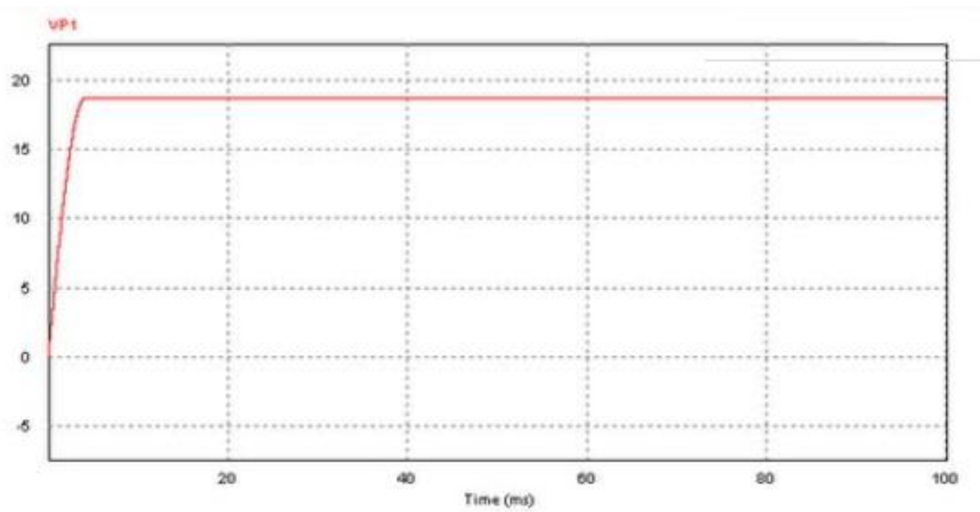

Figure 19 Rectifier output with capacitor

The single-phase diode rectifier was simulated using PSIM. The circuit is modeled in PSIM as shown in Figure 18 The theoretical voltage output form a single-phase diode rectifier is found by Vout=0.9Vin. Figure 19 illustrates the DC voltage output of the diode rectifier with the output capacitor.

INVERTER (OPEN LOOP UNIPOLAR PWM)

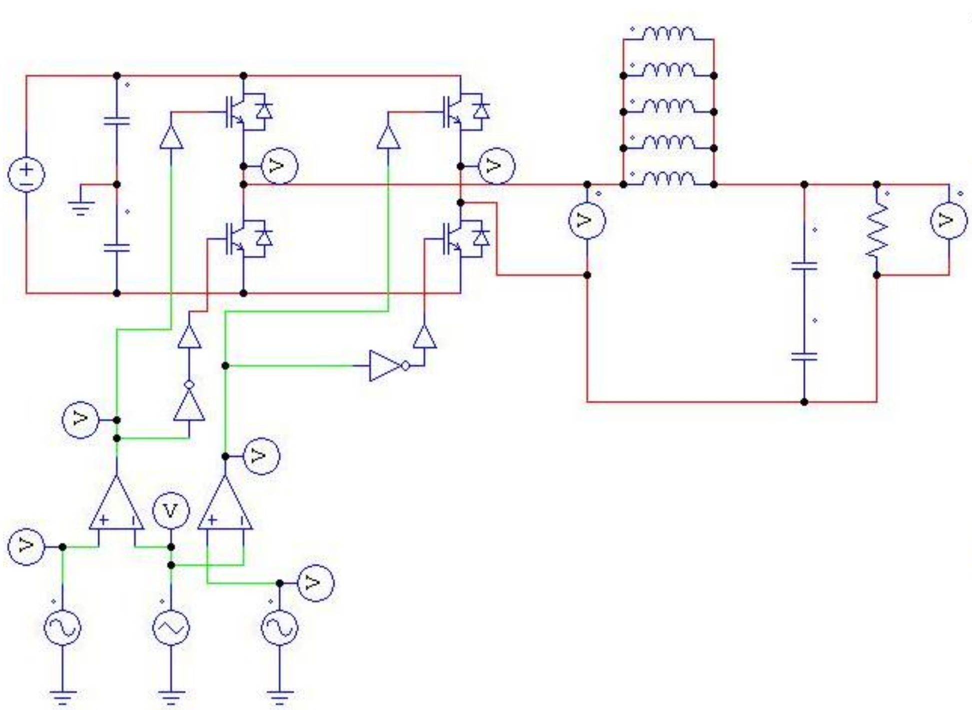

Figure 20 Single Phase inverter

Figure 20 shows the single phase inverter with an unipolar PWM scheme in a 200V DC input.

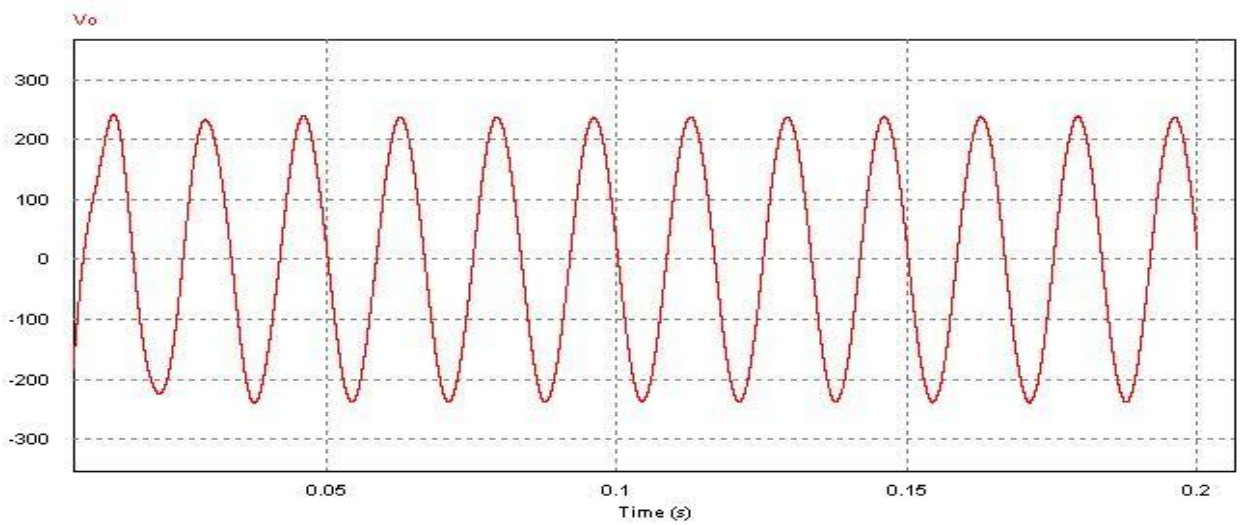

Figure 21 Inverter Output

The inverter output voltage, 60 Hz, 230 Vpeak can be observed throughout the simulation in Figure 21.

RESULTS

BRUSHLESS DC MOTOR

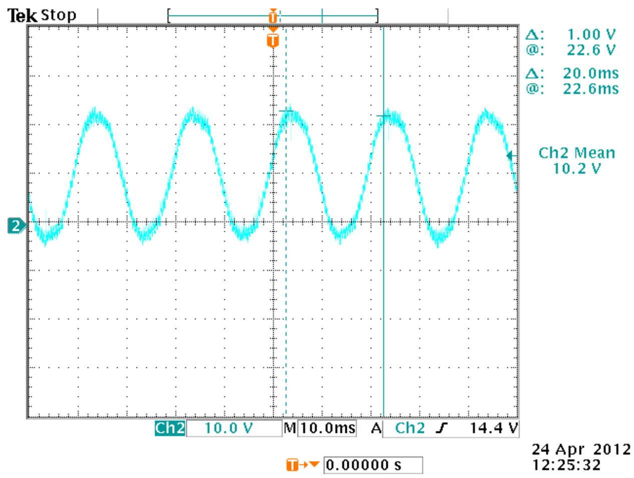

Figure 22 BLDC output voltage

Table 3 BLDC voltage outputs

Frequency	RPM	3-phase-to-neutral
5.00	150.0	2.40
20.0	600.0	19.5
40.0	1200	40.5
60.0	1800	61.0
80.0	2400	82.0
100	3000	87.0
120	3600	104

Figure 22 shows the actual output of one of the 3-phase legs of the brushless DC motor; this also concludes that our brushless DC motor has a sinusoidal output and not trapezoidal. Table 3 shows the various output voltages from 3-phase to-neutral at different frequencies and speeds.

RECTIFIER (BEFORE AND AFTER CAPACITOR FILTER)

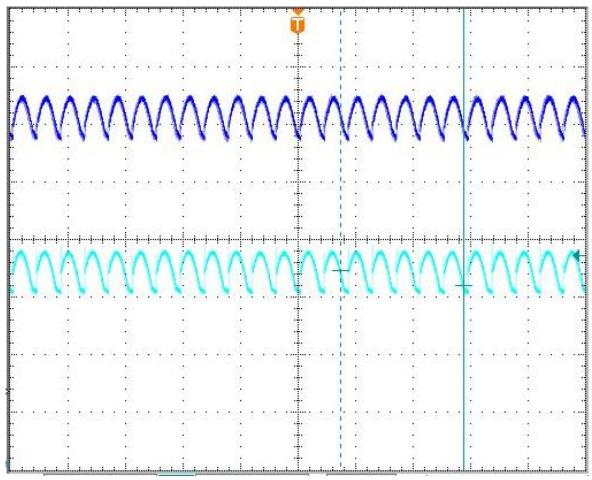

Figure 23 Rectifier output on oscilloscope without a capacitor

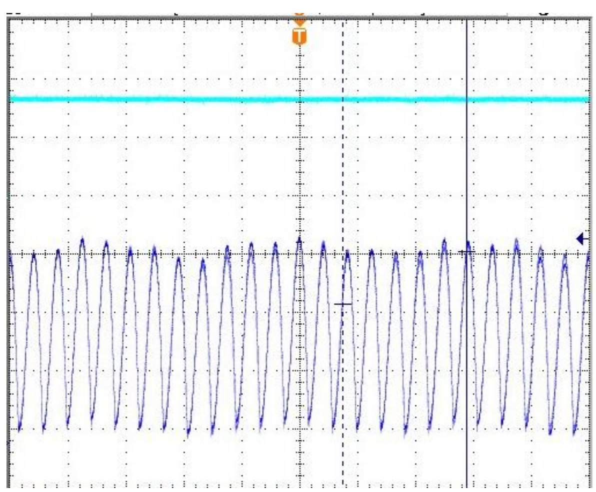

Figure 3 Rectifier output on oscilloscope with a capacitor

The figures 23 and 24 above are the output of the DC generator after the two rectifier conditions. In Figure 23, 24, the top dark blue line is current while the light blue is voltage. The values of the current and voltage are Vo=85.0V and Io=964mA at a speed of 3000RPM. As you can see, both signals are "bumpy" and we would like them to be smooth. In Figure 24, we can see the smooth output by using the output capacitor, 1500 μF. This particular figure 24 has the light blue is the DC voltage and the dark blue as 3 phase voltage. The values are Vin=64V, Vo=84 V and Io=961mA at a speed of 3000RPM. It's obvious that the Figure 24 has the smoother voltage signal than Figure 23. . Achieving this task was thanks to the capacitor value that we added. You can view the capacitor value in our Calculations section under Rectifier Capacitor Filter.

SINGLE BOOST (OPEN LOOP)

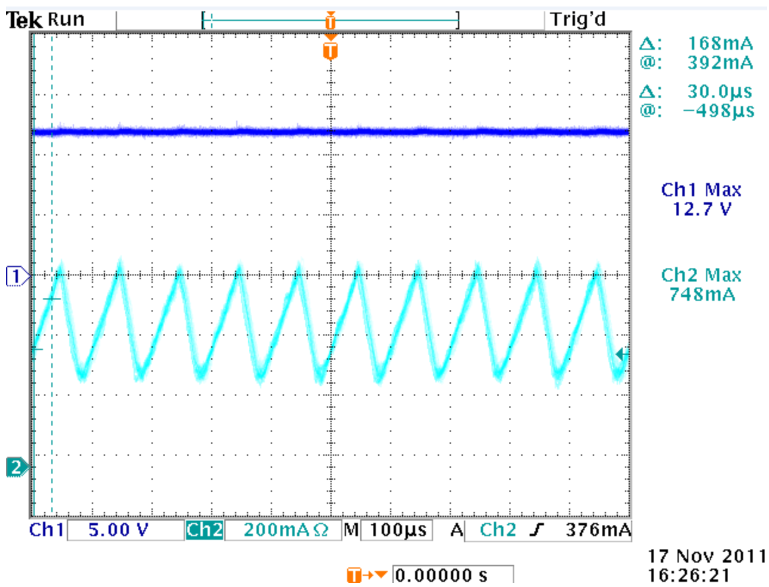

Figure 25 Boost converter at 60% duty cycle

Table 4 Boost converter output values

Input Voltage	Duty-cycle	Calculated Vo	Measured Vo	%Error
5	20%	6.25	6.52	4.32%
5	40%	8.33	8.40	0.84%
5	60%	12.5	12.7	1.60%
5	80%	25.0	24.5	2.00%

In Figure 25, you can see the output voltage of the boost converter in dark blue and the inductor current in light blue. Figure 25 shows that the 60% duty cycle matches the simulation values and the calculations from the equation of the boost converter mentioned above. Table 4compares the results from the lab and the actual calculated output voltages; we can see that the Vo increases as the duty cycle increases. We can also conclude that the Vo values are within reasonable percentages of error and do not exceed 5%. Overall we can conclude that the boost converter operated as expected and boosted the output voltage is within calculated and acceptable values.

INTERLEAVED BOOST (OPEN LOOP)

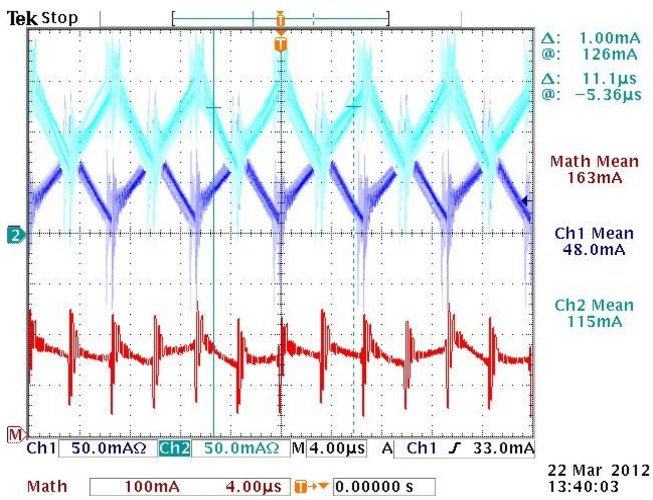

Figure 26 Inductor currents of interleaved boost converters at 50% duty cycle

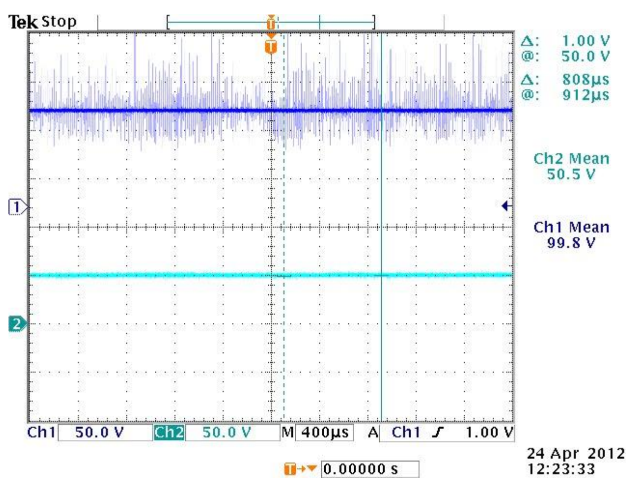

Figure 27 Vout and Vin of boost converter at 50% duty cycle

Figure 26 shows the inductor current of boost converter1 in dark blue, inductor current of boost converter 2 in light blue, and the output current of the inductors in red. From Figure 26, we can see that our simulation matches our actual lab outputs and that the inductor currents cancel each other ripples out and add their values. In Figure 27,you can see the output voltage of the boost converter in dark blue and the input voltage in light blue. From Figure 27, we can see that the input voltage to the boost converter is doubled as expected from the simulations and the equations used to calculate the output voltages.

GATE DRIVER

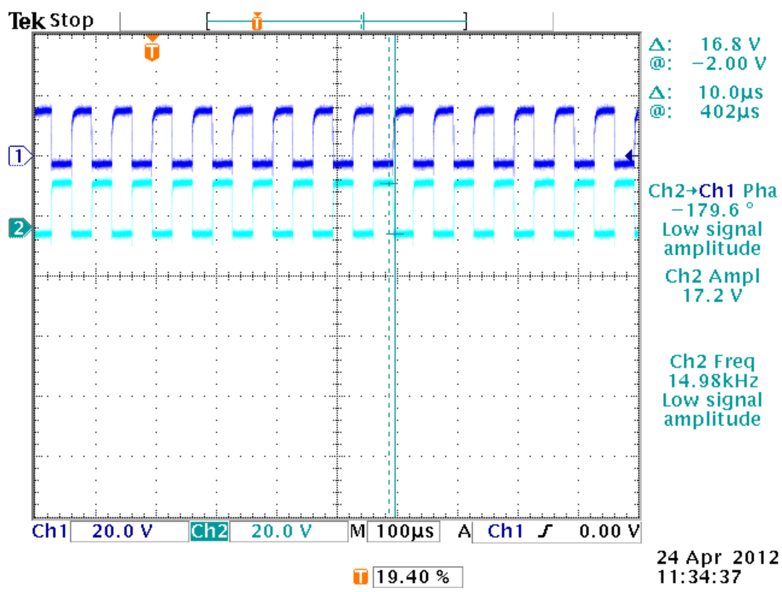

Figure 28 Vout of Gate Driver with 50% duty cycle

Figure 28 shows the output voltages of the gate driver with the dark blue signal 180 degrees out of phase of the light blue signal. This matches the simulation voltages mentioned above, the switch is due to the gate driver which is working correctly at 15 KHz.

BOOST (VOLTAGE AND CURRENT CLOSED LOOP)

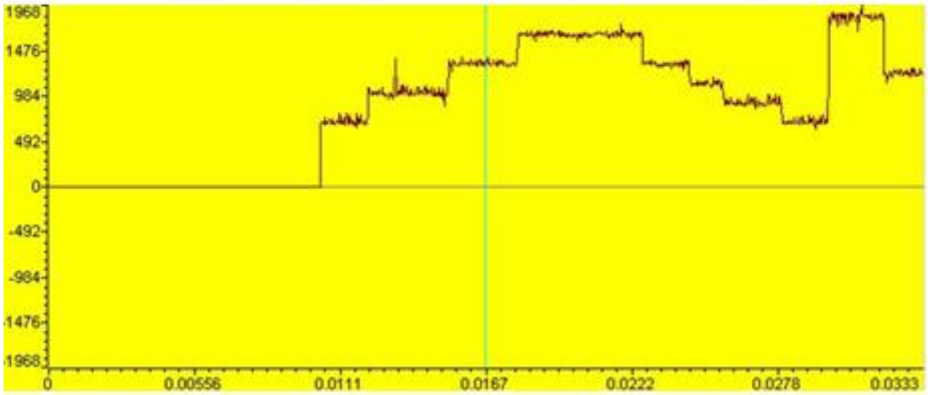

Figure 29 Output of closed loop controller

Figure 29 shows output of the closed loop controller of the boost converter as it was sensed by the ADC on the DSP. The plot is an output from Code Composer as the output voltage was being measured by the ADC on the DSP board. As it can be seen, the boost converter changes the output voltage when a new reference voltage is specified.

INVERTER (OPEN LOOP)

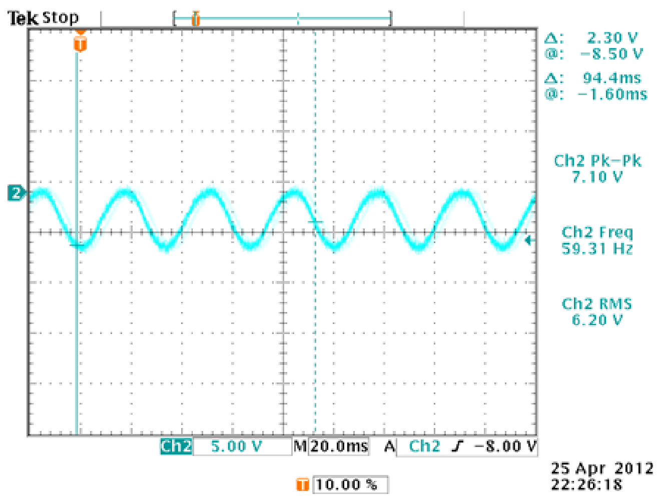

Figure 30 Inverter output

Figure 30 shows the inverter output voltage through the LC filer

CONCLUSION

Using small signal model of the system, the voltage and current controller for the system can be easily designed. The proposed controllers, the generator, the boost converter, and inverter are successfully implemented in a small scale 1kW permanent magnet generator based wind energy conversion system with DSP. In addition to being able to implement each subsystem building our own power supplie could be a big cost effective factor.. Throughout this year we encountered difficult circumstances, yet we overcome them. In the end we still have challenges to complete,. Overall, we the wind energy team are appreciative to our advisors and the Bradley University ECE program to allow us this opportunity and experience.

FUTURE WORK

As mentioned before, the system is working in single phase inverter. However, if this project were to continue it would need to be converted over to 3-phase inverter like most of the common applicatons in practice. This means the hardware would have to modify slightly. We would have to add to more IGBT's to our inverter. Also, additional work is needed on the inverter subsystem. In our project we were able to get it to work. The downside was that the signal wasn't the cleanest it could be. Thus, addition attention will be acquired in this field. In order to further improve the efficiency and reliability of the system, more advance controllers need to be implemented. A closed loop controller with maximum power point tracking (MPPT) algorithm[3,4] for the interleaved booster converter should be implemented so that the system outputs maximum power as seen in Figure 31.

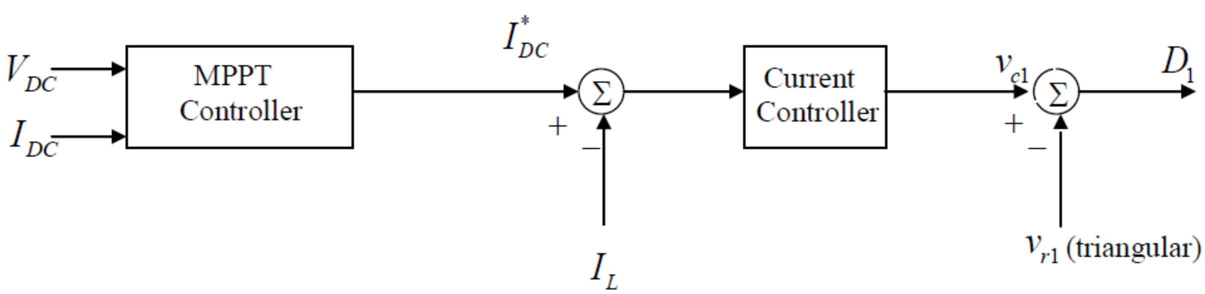

Figure 31 System Disgram of the closed loop controller with MPPT for the boost converter

Also, in order to integrate the system to the grid, a closed loop controller with power factor correction for the inverter should be implemented so that it can achieve unity power factor and be in phase with the grid current. The proposed system diagrams of the aforementioned controllers is shown in figure 32 We definitely feel as though we laid a solid foundation for other students to build upon.

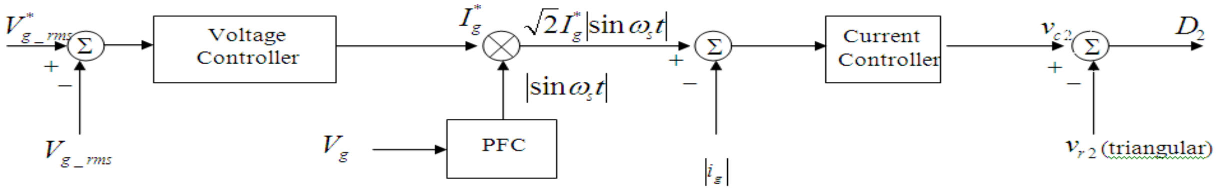

Figure 32 System Disgram of the closed Loop Controller for the inverter

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