Single-phase Variable Frequency Switch Gear

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EXECUTIVE SUMMARY

Single-phase variable frequency switch gear that uses an operator selected output frequency in the range of 1 to 60 Hz and a bipolar direct current (DC) voltage source will be designed, built, and tested. The single-phase variable frequency switch gear will generate a single-phase variable frequency output with a constant Volts/Hertz ratio. Design of the switch gear is limited by the following constraints: the switch gear must use a constant Volts/Hertz ratio, it must use devices rated for a current of 1.5 A_{RMS}, it must have a grounded neutral, and it must be safe. The switch gear should be reliable and efficient.

The single-phase variable frequency switch gear designed will contain components necessary for a variable frequency drive. Successful design of single-phase variable frequency switch gear can be extended to three phases, which will pave the way for design of a variable frequency drive. Variable frequency drives (VFD) vary the speed of three-phase alternating current (AC) induction motors by varying the frequency and voltage supplied to the motor. VFDs are important because they provide energy efficiency benefits to industries that consume large amounts of power operating AC machines.

Design and implementation of single-phase variable frequency switch gear will be accomplished through the design and implementation of its subsystems. Three subsystems will be designed, built, and tested. The first subsystem, a pulse-width modulated (PWM) generation controller, will take in a frequency select input in the range of 1 to 60 Hz to generate a switched PWM waveform. The second subsystem, gate drive circuitry, will amplify the voltage and current levels of the switched PWM waveform. The final subsystem, a DC-to-AC voltage inverter, will take a positive and negative DC voltage and convert it to AC voltages to generate a single-phase variable frequency output with a constant Volts/Hertz ratio.

Devices that will be used to build each subsystem are readily available at Bradley University. Any equipment needed for testing is available in the electrical engineering laboratories at Bradley University. The cost of building the proposed design for single-phase variable frequency switch gear is expected to be under $100.

The usefulness of variable frequency drives for energy efficiency is one motivation for designing single-phase variable frequency switch gear. Through the design of the switch gear, the design team expects to gain experience working with power electronics, which is another motivation for the design of variable frequency switch gear.

ABSTRACT

A variable frequency drive controls the speed of a three-phase alternating current motor by varying the frequency and voltage supplied to the motor. Variable frequency drives provide energy efficiency benefits to industries that consume large amounts of power operating alternating current (AC) machines. Single-phase variable frequency switch gear will be designed, built, and tested. Given an operator selected output frequency in the range of 1 to 60 Hz and a bipolar direct current (DC) voltage source, the variable frequency switch gear must provide the selected output frequency at the proper output voltage. Design of the single-phase variable frequency switch gear will be accomplished through the design of its subsystems. The subsystems are a software-based PWM generation controller, gate drive circuitry, and a DC-to-AC voltage inverter. Insulated gate bipolar junction transistor (IGBT) gate drive circuitry will be used to amplify voltage and current levels from the PWM generation controller, and to convert DC bus voltages to AC voltages in the DC-to-AC voltage inverter. Testing of the system will be conducted in the power laboratory at Bradley University.

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I. INTRODUCTION

A. Problem Background

A variable frequency drive (VFD) controls the speed of a three-phase alternating current (AC) motor by varying the frequency and voltage supplied to the motor [1]. When AC motors were introduced in 1888, motor speed control required either varying the magnetic flux or changing the number of poles on the motor. In contrast, direct current (DC) motor speed control could be achieved by inserting an external rheostat into the DC field circuit. In the 1980's VFD technology became reliable and inexpensive enough to compete with traditional DC motor control [2].

VFDs are important because they provide energy efficiency benefits to industries that consume large amounts of power. Through the use of VFDs, industries can match the speed of the motor driven equipment to the load requirements, rather than running the AC motor at full speed with variable speed mechanical drive trains [1]. Another benefit of using VFDs is the smooth startup of AC motors, which extends equipment life by reducing belt, gear, and bearing wear [3].

Previously at Bradley University, a senior project group designed and built a low-voltage single-phase variable frequency AC source using a LabVIEW based cDAQ controller from National Instruments to generate a switched pulse-width modulated (PWM) waveform [5]. Alternative software can be used to generate a switched PWM waveform.

B. Problem Statement

Single-phase variable frequency switch gear that will operate at an output voltage of 120 V_{AC} with frequencies between 1-60 Hz will be designed, built, and tested. The single-phase variable frequency switch gear will use a user-selected input frequency between 1 and 60 Hz and generate an output voltage with a constant Volts/Hertz ratio.

C. Constraints

Design constraints for the single-phase variable frequency switch gear are shown in Table I. The variable frequency switch gear must provide outputs frequencies in the range of 1-60 Hz. All devices used must be rated for a current of 1.5 A_{RMS}. The switch gear must be safe and must have a grounded neutral.

D. Scope

Table II lists what is in and out of scope for the design of the single-phase variable frequency switch gear. Single-phase operation is in scope, but three phase operation is out of scope. Generating output frequencies in the range of 1-60 Hz is in scope, but generating output frequencies greater than 60 Hz is out of scope. Driving a resistive load is in scope, but driving a 3-phace AC induction motor is out of scope.

TABLE I: CONSTRAINTS FOR SINGLE-PHASE VARIABLE FREQUENCY SWITCH GEAR

Constraints	
Output Frequencies	In the range of 1-60 Hz
Hardware	Devices rated for a current of 1.5 A_{RMS}
Safety	Safe to operate
Neutral	Grounded neutral

TABLE II: ITEMS THAT ARE IN AND OUT OF SCOPE OF THE DESIGN FOR SINGLE-PHASE VARIABLE FREQUENCY SWITCH GEAR

In Scope	**Out of Scope**
Single-phase operation	Three-phase operation
Output frequencies in the range of 1-60 Hz	Output frequencies greater than 60 Hz
Drive a resistive load	Drive an AC induction motor

I. STATEMENT OF WORK

A. System Description

1) System Block Diagram

The system block diagram of single-phase variable frequency switch gear system is shown in Fig. 1. The system has three inputs and one output. The inputs are a frequency select input and a bipolar DC source voltage. The output is a single-phase variable frequency voltage with a constant Volts/Hertz ratio.

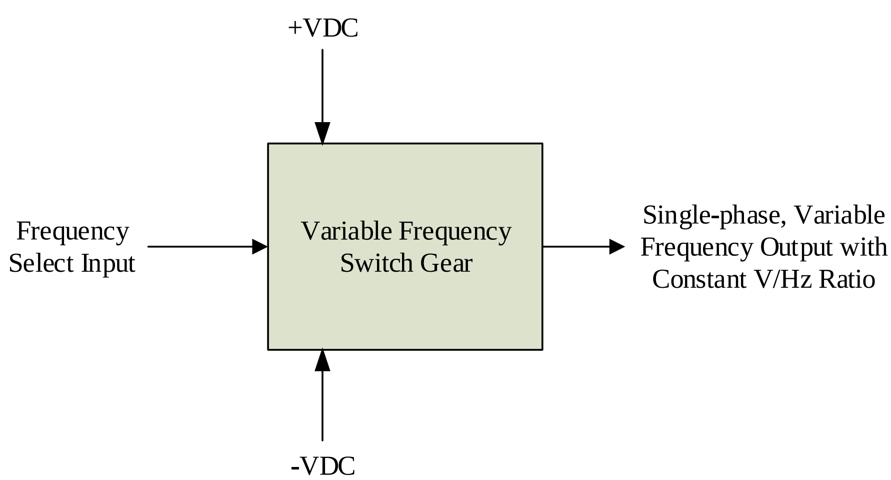

Fig. 1. System block diagram for single-phase variable frequency switch gear.

2) Subsystem Block Diagram

Design of single-phase variable frequency switch gear will be accomplished through design of its subsystems. A subsystem block diagram is shown in Fig. 2. A PWM generation controller will use a frequency select input to generate a switched PWM waveform. Gate drive circuitry will amplify the voltage and current levels of the PWM waveform to a useable level for the equipment used in the DC-to-AC voltage inverter. The DC-to-AC voltage inverter will convert DC bus voltages to AC voltages to generate a single-phase variable frequency output with a constant V/Hz ratio.

3) High-level Flowchart

The PWM generation controller in Fig. 2 will use software to generate a switched PWM waveform. A high-level flow chart for the PWM generation controller is shown in Fig. 3. The program will start and initialize timers. A 1 V peak-to-peak 15 kHz triangle wave and the desired half-wave rectified sine wave will be generated. The amplitude of these two waveforms will be compared. If the amplitude of the triangle wave is less than the amplitude of the sine wave, the output bit will be toggled high. If the amplitude of the triangle wave is greater than the amplitude of the sine wave, the output bit will be toggled low.

4) Nonfunctional Requirements

A list of objectives for the design of single-phase variable frequency switch gear is shown in Table III. The system should be reliable and the system should be efficient. As a first test to determine whether or not the system is reliable, the design team will look at how often the system returns the desired output. As a second test to determine whether or not the system is reliable, the design team will look at how long it takes for changes in the input to be seen in the output.

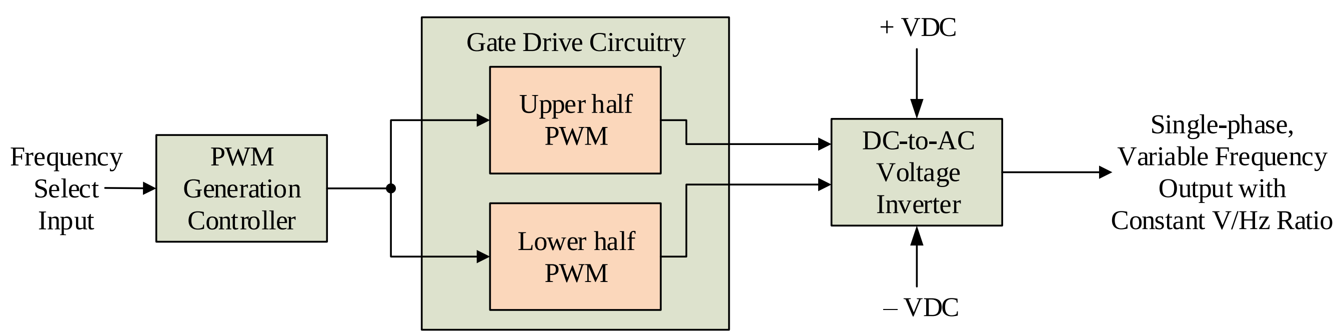

Fig. 2. Subsystem block diagram for single-phase variable frequency switch gear.

TABLE III: NONFUNCTIONAL REQUIREMENTS FOR SINGLE-PHASE VARIABLE FREQUENCY SWITCH GEAR

Objectives	
Reliable	The switch gear should be reliable
Efficient	The switch gear should be efficient

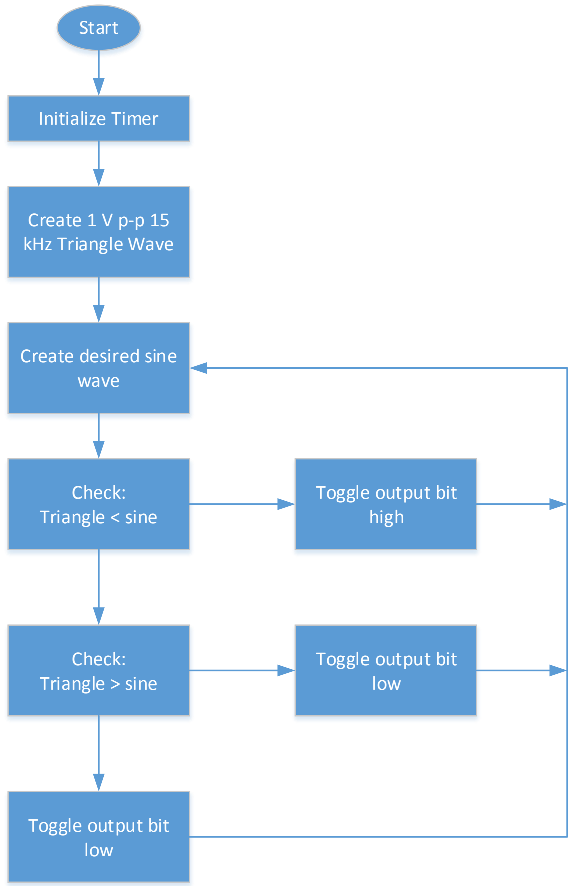

Fig. 3. High-level flowchart for PWM generation controller.

TABLE IV: FUNCTIONAL REQUIREMENTS AND CORRESPONDING SPECIFICATIONS FOR SINGLE-PHASE VARIABLE FREQUENCY SWITCH GEAR

System	Function	Specification
Overall	Provide a constant V/Hz ratio	±10 % tolerance
PWM Generation Controller	Generate a switched PWM waveform	±10 % tolerance
Gate Drive Circuitry	Amplify voltage and current levels from PWM generation controller	±10 % tolerance
DC-to-AC Voltage Inverter	Convert DC bus voltages to AC voltages	±10 % tolerance

5) Functional Requirements

Functional requirements for single-phase variable frequency switch gear are shown in Table IV. The overall system shall provide a constant V/Hz ratio. The constant V/Hz ratio should be within ±10 % tolerance of the expected value. The PWM generation controller shall generate a switched PWM waveform. Gate drive circuitry shall amplify voltage and current levels from the PWM generation controller. The amplitude of the amplified signal should be within ±10 % tolerance of the expected amplitude. The DC-to-AC voltage inverter shall convert DC bus voltages to AC voltages. The amplitude of the resulting sine wave from the DC-to-AC voltage inverter should be within ±10 % tolerance of the expected output voltage of 120 V_{AC}.

B. Design Approach and Method of Solution

Each subsystem will be discussed individually to describe the design approach and method of solution. A detailed testing plan will be discussed with each subsystem. Testing of the single-phase variable frequency switch gear will be conducted in the power laboratory at Bradley University. All equipment that will be used is readily available at Bradley University.

1) PWM Generation Controller

An Atmega128 Atmel AVR development board will be used to generate a switched PWM waveform. A 1 V peak-to-peak 15 kHz triangle wave and a half-wave rectified sine wave containing the desired frequency between 1-60 Hz will be generated. The amplitude of the triangle wave and half-wave rectified sine wave will be compared. If the amplitude of the triangle wave is greater than the amplitude of the sine wave, the bit on the output port will be toggled high. If the amplitude of the triangle wave is less than the amplitude of the sine wave, the bit on the output port will be toggled low. Every other half-cycle of the switched PWM output will control a separate bit on a given output port (e.g. PA0 and PA1).

To test operation of the PWM generation controller, an external digital to analog converter can be used to see the generated triangle wave and half-wave rectified sine wave with an oscilloscope. An oscilloscope can also be used to view the switched PWM output on the two bit.

The PWM generation controller is the key component to the design of single-phase variable frequency switch gear. If the Atmega128 cannot be programmed in a timely manner, then a function generator with LM311 comparators will be used as a substitute to generate a PWM signal that will drive IGBTs in the DC-to-AC voltage inverter.

2) Gate Drive Circuitry

Two Avago HCPL-3120 IGBT Gate Drive Optocoupler chips will be used. A gate drive with an optocoupler was chosen to protect the Atmega128 board from high voltages used in the DC-to-AC voltage inverter circuitry. The gate drive circuitry will use a high and a low side driver. Each driver will have an 18 V supply. One HCPL-3120 chip will be used for the high-side driver to drive the high-side IGBT in the DC-to-AC voltage inverter H-bridge. A second HCPL-3120 chip will be used for the low-side driver to drive the low-side IGBT in the DC-to-AC voltage inverter H-bridge.

To test the gate drive circuitry, a function generator will be used to provide a PWM signal for the gate drive circuitry. The output will be viewed from an oscilloscope to verify that the signal is amplified as desired.

3) DC-to-AC Voltage Inverter

A Fairchild FMG2G754560 IGBT pair will be used in the DC-to-AC voltage inverter to convert DC bus voltages to AC phase voltages. Positive and negative DC voltage rails will be used. The DC-to-AC voltage inverter will be made up of the H-bridge shown in Fig. 4. The output of the high-side driver from the gate drive circuitry will be the high-side PWM that will drive the upper IGBT of the H-bridge. The output of the low-side driver from the gate drive circuitry will be the low-side PWM that will drive the lower IGBT of the H-bridge. The output of the H-bridge will be connected to a resistive load connected to ground.

Testing of the DC-to-AC voltage inverter will not take place until the gate drive circuitry has been built and tested. To test the DC-to-AC voltage inverter, a function generator will be used to provide a PWM signal to the gate drive circuitry. The output of the gate drive circuitry will drive the IGBTs in the DC-to-AC voltage inverter. Power supplies available in the power laboratory at Bradley University will provide the positive and negative DC rails. The voltage levels at the output of a resistive load will be measured to determine if the IGBTs are switched as desired.

C. Economic Analysis

The total cost of parts is expected to be $81.97. The components and their respective prices are shown in Table V. The hardware components that will be utilized to complete the design of the single-phase variable frequency switch gear are an Atmega128 Atmel AVR development board, two Avago HCPL-3120 gate drivers, and a Fairchild FMG2G75US60 IGBT module. If the PWM generation controller cannot be successfully implemented with an Atmega128, LM311 comparators will be used.

The cost of an Atmega128A development board is $41.99 and is the most expensive part that is required to complete the project. Two Avago HCPL-3120 gate driver chips will be used. Each chip costs $3.27. The second most expensive part is the Fairchild FMG2G75US60 IGBT module, which costs $30. LM311 comparators can be found in packages of 10 for $3.44. The unit price for the comparator is $0.34.

The total cost could be minimized by using parts readily available at Bradley University. Parts readily available are the Atmega128, Avago HCPL-3120 chips, and Fairchild IGBT pair. Specifically, the Avago HCPL-3120 chips, Fairchild FMG2G75US60 IGBT, and the LM311 comparators are available through Professor Steven Gutschlag. The software programs that will be used are available to Bradley students on the desktop computers in the electrical engineering department. This eliminates the cost of software for the project. Any oscilloscopes and power supplies that will be used are accessible in Bradley University's power laboratory.

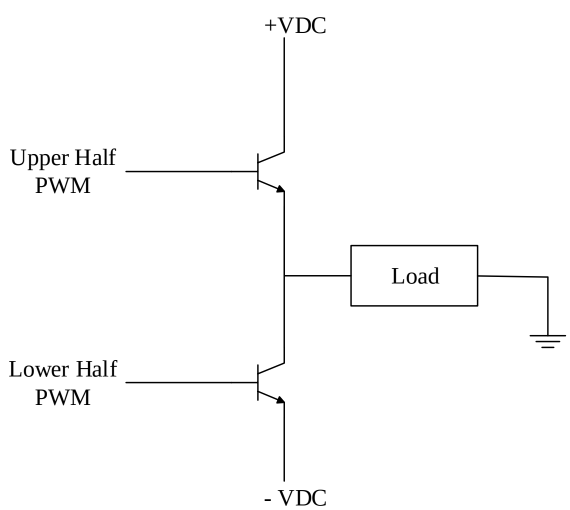

Fig. 4. H-bridge in the DC-to-AC voltage inverter with its output connected to a resistive load.

TABLE V: PARTS LIST FOR SINGLE-PHASE VARIABLE FREQUENCY SWITCH GEAR

Part	Cost	Quantity	Cost
Atmega128A Atmel AVR development board kit	$41.99	1	$41.99
Avago HCPL-3120	$3.27	2	$6.54
Fairchild FMG2G75US60 (IGBT)	$30	1	$30.00
LM311	$0.34	1	$0.34
Total Cost			$81.97

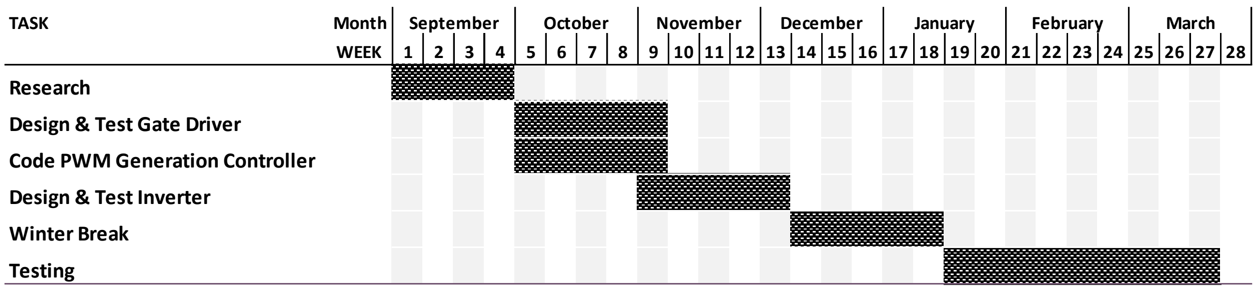

Fig. 5. Summarized Gantt chart for single-phase variable frequency switch gear.

D. Project Timeline

A summarized Gantt chart, shown in Fig. 5, depicts the project timeline. Design of variable frequency switch gear will be accomplished through design of its subsystems. Tasks have been assigned based on the subsystems that will be designed. Design of the PWM generation controller and gate drive circuitry will occur simultaneously. After the gate drive has been designed and built, the inverter will be designed and built. The design of the inverter is dependent on the gate drive as it inverts the output signal from the gate driver. Minor testing will occur as each subsystem is built.

The critical path of the tasks starts with the design and implementation of the PWM generation controller and gate drive circuitry. The testing of the DC-to-AC voltage inverter is dependent on successful implementation of gate drive circuitry. Therefore, testing of the DC-to-AC voltage inverter will occur after testing of gate drive circuitry. Testing of the overall system is dependent on successful implementation of each subsystem.

The largest portion of work is in the building and the testing of each subsystem. Testing of the switch gear is predicted to take up the majority of the second semester. Testing is scheduled for the second semester due to the dependency on completion of the hardware and software design. The testing task also includes any minor redesigning that needs to take place. A full Gantt chart is shown in Fig. 1 in appendix A.

E. Division of Labor

Each member is responsible for a different portion of the project. Leslie will be primarily responsible for the design of gate drive circuitry and the DC-to-AC voltage inverter. Eric is responsible for the design and programming of the PWM generation controller. Both members will work on interfacing the software and hardware that has been completed. This includes connecting the gate drive circuitry and DC-to-AC voltage inverter to the Atmega128 board and using the generated code for the PWM generation controller. Lastly, the testing and any minor design changes will be carried out by both team members. A table displaying the division of labor is included in Table I in the appendix A.

F. Societal and Environmental Impacts

The use of a variable frequency drive impacts industries that consume large amounts of power operating AC machines. The smooth startup to AC motors that VFDs provide increases the lifespan of equipment by reducing belt, gear, and bearing wear. Smooth startup also reduces shaft fatigue to the motor. The less frequent a piece of equipment needs to be replaced positively benefits a company since there is less turnover of equipment. Matching the speed of the motor to load requirements rather than using variable speed mechanical drive trains increases efficiency. An increase in efficiency decreases the power consumption. The environmental impact of less power consumption means there are lower amounts of pollution produced.

There are several safety standards that are used for power drive systems to reduce risk of operating equipment. The UL-61800-5-1 standard refers to adjustable speed electric drive systems and the NEC, NFPA 70E standard refers to reducing exposure to major electrical hazards.

II. CONCLUSIONS

Single-phase variable frequency switch gear will be designed, built, and tested. The switch gear will use an operator selected output frequency in the range of 1 to 60 Hz and a bipolar DC voltage source to generate a single phase variable frequency output with a constant Volts/Hertz ratio. Three subsystems will be constructed to accomplish the design of the switch gear. The subsystems are a PWM generation controller, IGBT gate drive circuitry, and a DC-to-AC voltage inverter.

All equipment used is readily available at Bradley University. Testing of the system will be done in the power laboratory at Bradley University.

Successful design of single-phase variable frequency switch gear can be extended to three phases, which would pave the way for design of a variable frequency drive.

III. REFERENCES

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A. SCHEDULE

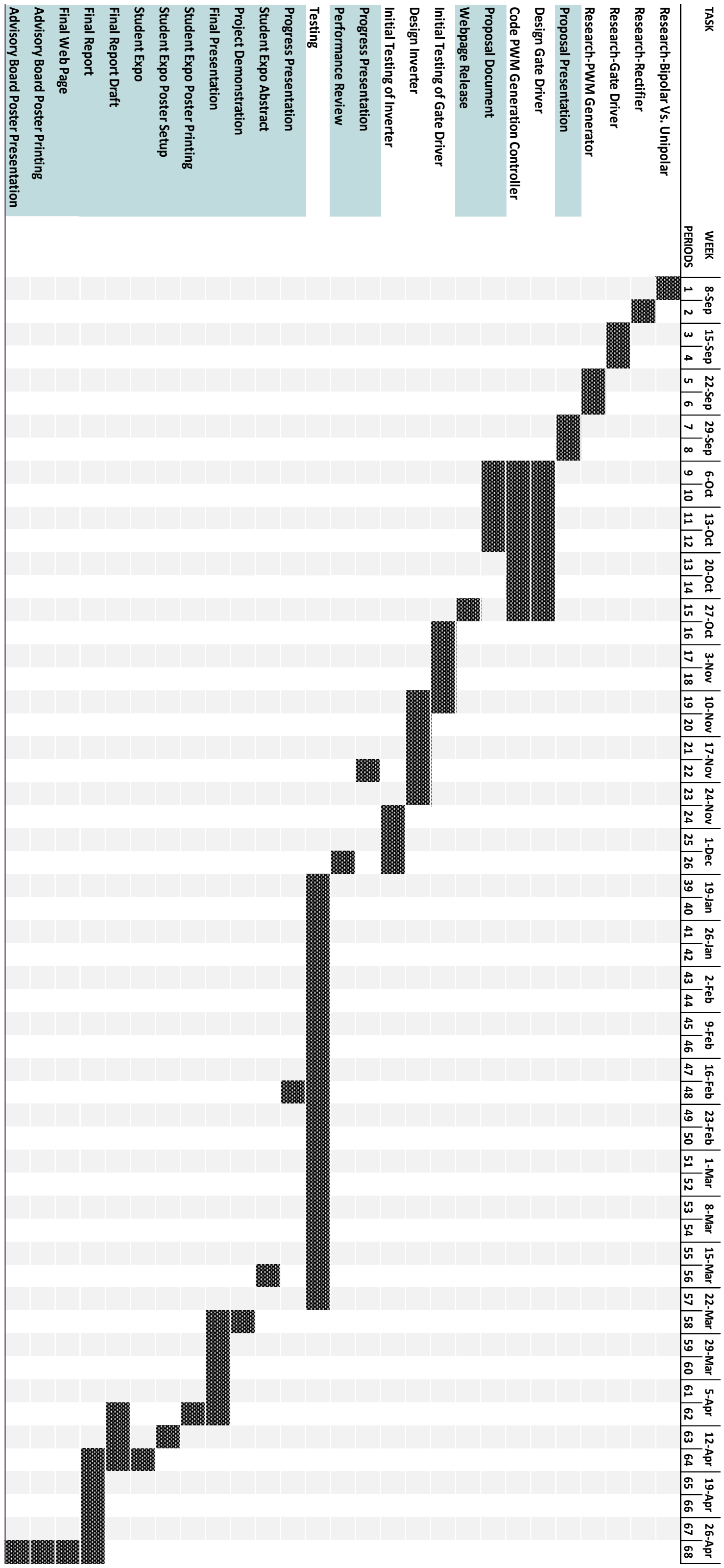

Fig. 1. Gantt Chart for single-phase variable frequency switch gear

TABLE I: SCHEDULE FOR SINGLE-PHASE VARIABLE FREQUENCY SWITCH GEAR

TASK	START DATE	END DATE
Research-Bipolar Vs. Unipolar	9/8/2015	9/9/2015
Research-Rectifier	9/10/2015	9/11/2015
Research-Gate Driver	9/15/2015	9/17/2015
Research-PWM Generator	9/22/2015	9/24/2015
Proposal Presentation	9/29/2015	10/1/2015
Design Gate Driver	10/6/2015	10/27/2015
Code PWM Generation Controller	10/6/2015	10/27/2015
Proposal Document	10/6/2015	10/15/2015
Webpage Release	10/27/2015	10/28/2015
Simulate Gate Driver	10/29/2015	11/3/2015
Design Inverter	11/3/2015	11/17/2015
Simulate Inverter	11/17/2015	11/19/2015
Build Components	11/24/2015	12/1/2015
Progress Presentation	11/19/2015	11/19/2015
Performance Review	12/3/2015	12/3/2015
Testing	1/19/2016	3/22/2016
Progress Presentation	2/18/2016	2/18/2016
Student Expo Abstract	3/18/2016	3/18/2016
Project Demonstration	3/24/2016	3/24/2016
Final Presentation	3/24/2016	4/7/2016
Student Expo Poster Printing	4/11/2016	4/11/2016
Student Expo Poster Setup	4/12/2016	4/12/2016
Student Expo	4/14/2016	4/14/2016
Final Report Draft	4/7/2016	4/14/2016
Final Report	4/14/2016	4/28/2016
Final Web Page	4/28/2016	4/28/2016
Advisory Board Poster Printing	4/28/2016	4/28/2016
Advisory Board Poster Presentation	4/29/2016	4/29/2016

B. NONFUNCTIONAL REQUIREMENTS

Metrics for Reliability are as follows:
Units: Design team's assessment of reliability from 0 (worst) to 10 (best)
Metrics: Points will be assigned based on the following scale

Always gives desired output	10
Almost always gives desired output	6.6
Almost never gives desired output	3.3
Never gives desired output	0

Metrics for efficiency are as follows:
Units: Design team's assessment of efficiency from 0 (worst) to 10 (best)
Metrics: Points will be assigned based on the following scale shown in Table I

TABLE I: POINTS ASSIGNED FOR LEVEL OF EFFICIENCY IN SINGLE-PHASE VARIABLE FREQEUNCY SWITCH GEAR

Time it takes for changes in input to be seen in the output (milliseconds)	**Value Scale**
≤ 10	10
≤ 20	6.6
≤30	3.3
>30	0