Design and Simulation of Three Phase Controlled Rectifier Using IGBT

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Abstract

An electric power can be converted from one form to another form by using power electronics devices. The function of power electronics circuits by using semiconductor devices as switch is modifying or controlling a voltage. The goal of power electronics circuits are to convert electrical energy from one form to another, from source to load with highest efficiency, high availability and high reliability with the lowest cost, smallest size and weight. The term rectification refers to the power circuit whose function is to alter the ac characteristic of the line electric power to produce a “rectified” ac power at the load side that contains the dc value. Rectifiers are used to convert the AC voltage into DC or low-frequency AC to supply the different combinations of the load like the resistance and the Inductance. In this project task, the rectifier circuit should be possible to produce a variable average voltage by controlling the delay of 60°. A versatile method of controlling the output of a full-wave rectifier is to substitute controlled switches such as IGBTs for the diodes. This paper introduces the characteristics of the three-phase full-controlled bridge rectifier circuit, and MATLAB / Simulink module for the full control of three-phase bridge rectifier circuit is narrated briefly, the model for the three-phase bridge full-controlled rectifier circuits has been made, MATLAB software were used for different firing angle, a different trigger pulse when the circuit was simulated the output waveform when the firing angle change, or 6 pulses synchronized trigger pulse width is changed. The output is controlled by adjusting the delay angle of each IGBT, resulting in an output voltage or output current which is variable over a limited range with programmed the Arduino UNO R3.

Keywords: Arduino, MATLAB software, IGBT, three phase controlled rectifier, Rectifier.

1. INTRODUCTION

The modern era of power electronics began in 1958, when the General Electric Company introduced a commercial thyristor, two years after it was invented by Bell Telephone Laboratory. Soon all industrial applications that were based on mercury-arc rectifiers and power magnetic amplifiers were replaced by silicon-controlled rectifiers (SCRs). In less than 20 years after commercial SCRs were introduced significant improvements in semiconductor fabrication technology and physical operation were made, and many different types of power semiconductor devices appeared. The function of power electronics circuits by using semiconductor devices as switch is modifying or controlling a voltage. The goal of power electronics circuits is to convert electrical energy from one form to another, from source to load with highest efficiency, high availability and high reliability with lowest cost, smallest size and weight.

There are four conversion circuits as shown in Figure-1 that are used in the majority of today’s power electronics circuits. Firstly are ac-to-ac, secondly is ac-to-dc, thirdly is dc-to-ac and the last is dc-to-dc. In terms of functional description, modern power electronics system performs one or more of the following conversion functions.

Figure 1-Four Types of Conversion
2. METHODOLOGY

The objective or the purpose of this project is the important part of getting started because it will drive to the outcomes of this project. Basically there are two main purpose which are, firstly to explore and learn the operation of Arduino UNO to control thyristor circuit and secondly to build and test the circuit. Besides the two main objectives there are also other outcomes that need to be reach at the end of this project such as to produce DC voltage or current with low ripple and to reduce the output close to the theoretical value. This project concentrates on a development of a circuit and hardware to get dc output using IGBT and Arduino UNO as main component of the project. Besides the scopes is to program an arduino to control delay angle ($\alpha$) and it produced variable outputs.\[1\]

To develop the whole project, it consists of three methods which are the concept of switching, the electrical structure, and the software programming. After designing and building completely the rectifier circuit, the driver circuit should be able to control the delay angle $\alpha$, that can be adjusted by using microcontroller. It will involve the programming development to control the ON state of the power switch and adjust the phase angle. Here, the trigger angle of IGBTs will be programmed in certain time sequence to ensure the input voltage goes from low to full voltage.

3. THREE PHASE CONTROLLED RECTIFIER

In the section 3.1, we will discuss about how the modeling and simulation of a power electronic converter can be carried out using MATLAB/SIMULINK software and in section 3.2 we will define important parameters to understand the performance of single and 3-$\Omega$ rectifiers.

3.1 MATLAB-Simulink for Power Electronics

In this section we will study about the modeling and simulation method for the power electronics circuits. SimPowerSystems provides component libraries and analysis tools for modeling and simulating electrical power systems. The libraries offer models of electrical power components, including three-phase machines, electric drives, and components for applications such as flexible AC transmission systems (FACTS) and renewable energy systems. SimPowerSystems models can be used to develop control systems and test system level performance. To deploy models to other simulation environments, including hardware-in-the-loop (HIL) systems, SimPowerSystems supports C-code generation.\[8\] SimPowerSystems contains application libraries, Electrical Sources (Contains blocks that generate electric signals), Elements (Contains linear and nonlinear circuit elements.), Extra Library (Contains three-phase blocks and specialized measurement and control blocks. You can also open this library by entering powerlib_extras at the command line.), Machines (Contains power machinery models.), Measurements (Contains blocks for the current and voltage measurements.), Power Electronics (Contains power electronics devices.) and powergui (used to decide supply; i.e. continues or discrete) libraries to design and stimulate different power electronics circuits. THYRISTOR, MOSFET, GTO, AC/DC VOLTAGE supply are one of the examples of various libraries blocks.

3.2 Performance parameters for Rectifiers

Before starting to examine different topologies for single-phase or multi-phase rectifiers, we should define some parameters. These parameters are needed to compare the performances among the different structures.

Let us assume we have ideal switches (diodes or thyristors) with zero commutation time (i.e., instantaneous turn on and off) and zero on-resistance (i.e., when conducting they present neither voltage drop nor losses). The load itself is an ideal resistance. The generic scheme is shown in Figure 2. At the input of the rectifier there are one or more AC voltages from the secondary of the transformer. At the output of the rectifier, on the load, there is also a time-dependent voltage. This voltage, as will be shown, is a combination of the voltages at the input of the rectifier stage.\[2\]

The DC voltage on the load is the average over the period $T$ of the output voltage of the rectifier:
Similarly, it is possible to define the R.M.S. voltage on the load:

\[ V_L = \sqrt{\frac{1}{T} \int_0^T v_L^2(t) \, dt} \]  

(2)

The ratio of the two voltages is the Form Factor (FF):

\[ FF = \frac{V_L}{V_{\text{DC}}} \]  

(3)

This parameter is quite important since it is an index of the efficiency of the rectification process. Having assumed the load to be purely resistive, it is possible to define the currents as

\[ i_L(t) = \frac{v_L(t)}{R_L} \]

\[ I_{\text{DC}} = \frac{V_{\text{DC}}}{R_L} \]  

(4)

\[ i_L = \frac{V_L}{R_L} \]

(5)

The rectification ratio (\(\eta\)), also known as rectification efficiency, is expressed by

\[ \eta = \frac{P_{\text{DC}}}{P_L + P_D} \]

where

\[ P_{\text{DC}} = V_{\text{DC}} \cdot I_{\text{DC}} \]

\[ P_L = V_L \cdot I_L \]

\[ P_D = R_D \cdot i_L^2 \]  

(6)

Hence we get,

\[ \eta = \frac{V_{\text{DC}} \cdot I_{\text{DC}}}{V_L \cdot i_L + R_D \cdot i_L^2} = \frac{V_{\text{DC}}^2}{V_L^2} \cdot \frac{1}{1 + \left(\frac{R_D}{R_L}\right)} \]  

(7)

We have assumed ideal switches, with no losses, that is \(R_D = 0\). Therefore

\[ \eta = \left(\frac{V_{\text{DC}}}{V_L}\right)^2 = \left(\frac{1}{FF}\right)^2 \]  

(8)
The Ripple Factor (RF) is another important parameter used to describe the quality of the rectification. It represents the smoothness of the voltage waveform at the output of the rectifier (we have to keep in mind that our goal is to obtain a voltage and a current in the load as steady as possible). The RF is defined as the ratio of the effective AC component of the load voltage versus the DC voltage:

\[
RF = \sqrt{\frac{V_1^2 - V_2^2}{V_{DC}}} = \sqrt{FF^2 - 1}.
\]

A transformer is most often used both to introduce a galvanic isolation between the rectifier input and the AC mains and to adjust the rectifier AC input voltage to a level suitable for the required application. One of the parameters used to define the characteristics of the transformer is the Transformer Utilization Factor (TUF):

\[
TUF = \frac{P_{DC}}{\text{Effective Transformer VA Rating}} = \frac{P_{DC}}{\frac{V_{Ap} + V_{As}}{2}}
\]

where VAP and VAS are the power ratings at the primary and secondary of the transformer. It should be noted that some use only the term VAS as ‘Effective Transformer VA Rating’. Here, a more complete definition, the average of primary and secondary VA ratings, has been chosen. This is why different TUF values are found in the literature for those topologies—the ‘single-way’ ones—with different power ratings at primary and secondary.

In order to compare the different topologies, it is useful to also take into consideration some parameters related to the switches—diodes or thyristors—like, for example, the Peak Inverse Voltage (PIV) during the blocking state of the device or the maximum current in the load. In practice, one has to choose devices with a peak repetitive reverse voltage (VRRM as reported on the data sheets) and a peak repetitive forward current (IFRM) higher than the PIV and maximum load current.

### 3.3 Phase Angle Delay Control

Converter operation in steady-state is best described over a period that begins from the phase \(\alpha\) to \(\pi + \alpha\). This operation involves two circuit modes during a single period of the source waveform depending upon the state of the switches as shown in Figure 3. Mode 1 starts when the IGBTs T1 and T3 are turned on at an angle \(\alpha\) by control pulses applied at their gate terminals. During mode 1, IGBTs T1 and T3 are in forward-biased mode and IGBTs T2 and T4 are in reverse blocking mode. The current \(I_o\) flows through the path shown in Figure 3. After angle \(\pi\), the input source voltage become negative but the IGBTs T1 and T3 still conducting. Note that the current sink is the model of a high value inductor, voltage across it can change instantaneously but current cannot. Hence, the output voltage, \(V_o\) become negative and follows the input voltage, \(V_s\) waveform. The input source is supplying power to the load during \(\alpha\) to \(\pi\) which is referred also as the rectifier operation.[4]

![Figure 3 Circuit Modes](image)
Mode 2 begins when the IGBTs T2 and T4 are turned on at an angle $\alpha + \pi$ by the control pulses applied at their terminals. The current is steered away from the IGBTs T1 and T3 to T2 and T4 effecting a natural commutation. Now thyristors T1 and T3 are in reverse blocking mode. This converter operation in this mode is identical to that mode 1 during the angle from $\pi + \alpha$ to $2\pi + \alpha$. There several possible output voltages are shown in Figure 5 given duty ratio of 50%. The phase delay angle allows control over the DC output just as duty ratio control permits adjustment of the output in DC-DC converter. Since DC output is of interest and because the output current comes along with a DC source, the average voltage $V_o$ needs to be determined. Its value will be:

$$V_o = \frac{1}{\pi} \int_{\alpha}^{\alpha + \pi} V_m \sin(\omega t) \phi dt = \frac{2V_m}{\pi} \cos \alpha$$

![Figure 4](image-url) - Possible Output Voltage waveform For SCR Bridge

4. **PROBLEM IDENTIFICATION**

A rectifier is an electronic circuit that converts bidirectional voltage (AC voltage) to unidirectional voltage (DC voltage) by using power diodes or by controlling the firing angle of thyristor / controllable switches. Rectifier usually can be divided into two types that are uncontrolled and phase-controlled. Each type can have either single phase or three-phase. A diode is the simplest electronics switch which it is uncontrolled that the on and off states can be determined by the power supply in the circuit itself. AC to DC converter is mostly used in industries and also in domestic equipment. But many rectifiers in the market only produce fixed output so the applications of the rectifiers are limited for certain equipment only. So, the DC level of the output and the power transferred to the load are fixed when the source and load parameters are established.[1]

Hence, to overcome this problem there is a way to control the output voltage of the rectifier. Basically, the single phase rectifier is designed using the thyristors or more specifically are called Silicon Control Rectifier (SCR) and with insulated gate bipolar transistors (IGBT) which connected in full-wave rectifier. A thyristor is four layers (pnpn) semiconductor devices that act as switches, rectifiers or voltage regulators. Thyristors are electronic switches used in power electronics circuits where control of switch turn-on is required. Thus, the output voltage can be variable from the range of zero voltage to full voltage by controlling the delay angle of the IGBT.

5. **ARDUINO UNO**

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. You can tell your board what to do by sending a set of instructions to the microcontroller on the board. To do so you use the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on Processing [6].

"Uno" means one in Italian and was chosen to mark the release of Arduino Software (IDE) 1.0. The Uno board and version 1.0 of Arduino Software (IDE) were the reference versions of Arduino, now evolved to newer releases. The Uno board is the first in a series of USB Arduino boards, and the reference model for the Arduino platform; for an extensive list of current, past or outdated boards see the Arduino index of boards.

- Inexpensive
- Cross-platform
- Simple, clear programming Open source and extensible software
• Open source and extensible software
• Open source and extensible hardware

5.1 Technical parameters

<table>
<thead>
<tr>
<th>Table 1 Technical Specification of Arduino UNO R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
</tr>
<tr>
<td>Operating Voltage</td>
</tr>
<tr>
<td>Input Voltage (recommended)</td>
</tr>
<tr>
<td>Input Voltage (limit)</td>
</tr>
<tr>
<td>Digital I/O Pins</td>
</tr>
<tr>
<td>PWM Digital I/O Pins</td>
</tr>
<tr>
<td>Analog Input Pins</td>
</tr>
<tr>
<td>DC Current per I/O Pin</td>
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<tr>
<td>DC Current for 3.3V Pin</td>
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<tr>
<td>Flash Memory</td>
</tr>
<tr>
<td>SRAM</td>
</tr>
<tr>
<td>EEPROM</td>
</tr>
<tr>
<td>Clock Speed</td>
</tr>
<tr>
<td>LED_BUILTIN</td>
</tr>
</tbody>
</table>

5.2 Arduino Output for Gate Pulse

Figure 5-9 shows the gate pulse given to the Driver Circuit of the three phase controlled rectifier where Gate-1 pulse is taken as a reference to compare other gate pulse:

![Figure 5 G1-G2](image)

![Figure 6 G1-G3](image)
6. **Simulation in MATLAB**

In this section, using MATLAB SIMULINK simulation the Three phase controlled Rectifiers is done. Following are the results of the simulation. Figure 10-12 shows the Model file, pulse generator of six IGBT's, output waveform of three phase controlled rectifier in MATLAB Simulink respectively. [5]
Figure 11-Gate triggering ($\alpha = 60^\circ$)

Figure 12-Output Waveform of Three phase Full Wave controlled rectifier with R load

7. THRISTOR TRIGGERING

Table 1 shows the Gate triggering in degree and in seconds.[3]

- The thyristors are triggered at an interval of ($\pi$/3) radians (i.e. at an interval of 30°)
- The frequency of output ripple voltage is 6fs.

Table 2 Gate Triggering

<table>
<thead>
<tr>
<th>NO.</th>
<th>Thyristor</th>
<th>FIRING ANGLE IN DEGREE</th>
<th>FIRING ANGLE IN SECOND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1</td>
<td>60</td>
<td>3.33e-3</td>
</tr>
<tr>
<td>2</td>
<td>T2</td>
<td>120</td>
<td>6.67e-3</td>
</tr>
</tbody>
</table>
8. Prototype of Three Phase Controlled Rectifier Using IGBT

Figure 13-14 shows the hardware of driver circuit and hardware of power circuit respectively. Figure-15 shows the prototype of three phase controlled rectifier using IGBT.

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<tbody>
<tr>
<td>3</td>
<td>T3</td>
<td>180</td>
<td>10e-3</td>
</tr>
<tr>
<td>4</td>
<td>T4</td>
<td>240</td>
<td>13e-3</td>
</tr>
<tr>
<td>5</td>
<td>T5</td>
<td>300</td>
<td>16.67e-3</td>
</tr>
<tr>
<td>6</td>
<td>T6</td>
<td>360</td>
<td>20e-3</td>
</tr>
</tbody>
</table>

Figure 13- Hardware of Driver Circuit

Figure 14- Hardware of Power Circuit

Figure 15 Prototype of the Project
9. Future Work

As per the future work the MCT, TRIAC, GTO, etc. can be used for the higher frequency and high speed of operation in place of IGBT & SCR. They can be used for the high current and voltage ratings.

Following are the power ratings for different switches:

- Low power application : GTO, IGBT, Power BJT, Power MOSFET etc.
- High power application : Thyristor or SCR.

To smooth the output of the rectifier a reservoir capacitor is used. IGBT’s have replaced SCR is almost all applications except at very high current and voltage, where SCRs still have a cost advantage. IGBT's higher switching frequency also has big advantage of higher control bandwidth.

10. Conclusion

The project was aimed at design and simulation of three phase controlled rectifier. Accordingly, the three phase controlled rectifier has been designed for the required specifications and the necessary hardware has been developed, assembled and tested. The hardware setup of the project consists of:

- Power Circuit of Controlled Rectifier
- Driver Circuit
- Gate control circuit (ARDUINO UNO R3)
- Three phase supply

It has been observed in this project that the output obtained is of 6-pulse ripple current or voltage. The IGBT can be controlled by different firing angles (i.e; 30°, 60°, 90°, etc.). In this project had controlled the IGBT at 60°.

References

[8] R.W. Wall and H.L. Hess, Design and microcontroller implementation of a three-phase SCR power converter, Idaho University, Department of Electrical Engineering

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