Firing circuits for three-phase power electronic circuits

by Tai-Ming Timmious Lee

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
This thesis reports upon the design of three different firing angle controller circuits for controlling three-phase voltages and compares them. These circuits will be used by the students to do controlled experiments in the Power Electronics Laboratory of the Electrical Engineering Department at Montana State University. The three circuits are a phase-shifter-based three-phase voltage controller; a ramp-comparator-based three-phase voltage controller and a phase-locked-loop based three-phase voltage controller. The phase-shifter-based controller is a nonlinear firing angle controller, and the other two controller circuits are linear firing angle controllers. All operate at 60Hz controllers. With the aid of a SPICE simulation, the error of the ramp-comparator circuit has been minimized by means of an error blocking circuit added to block the discharging error of the ramp-comparator circuit. The ramp-comparator-based controller may have different errors for each channel. The phase-locked-loop controller consists of a ramp-comparator circuit and a phase-locked-loop circuit. It has the advantage of equal error per channel, and the error may be reduced by changing the free running frequency of the phase-locked-loop. The firing angle can be controlled linearly by changing the reference voltage of the ramp-comparators. For the phase-locked-loop based voltage controller, the possible range of the firing angle may be from 0° to 180° with much less than 1° error. The theoretical error formulas are derived, and the experimental results of the designed controllers are presented. The application of phase-locked-loop in three-phase inverter design is also discussed in this thesis.

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APPROVAL

of a thesis submitted by

Tai-Ming Timmious Lee

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

11-28-88

Date — Chairperson, Graduate committee

Approved for the Major Department

11-28-88

Date — Head, Major Department

Approved for the College of Graduate Studies

12/21/88

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Date 11/28/88

DEDICATION

I dedicate this thesis as a memorial to my grandfather, Mr. Ying-Fu Lee.

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ABSTRACT

This thesis reports upon the design of three different firing angle controller circuits for controlling three-phase voltages and compares them. These circuits will be used by the students to do controlled experiments in the Power Electronics Laboratory of the Electrical Engineering Department at Montana State University. The three circuits are a phase-shifter-based three-phase voltage controller; a ramp-comparator-based three-phase voltage controller and a phase-locked-loop based three-phase voltage controller. The phase-shifter-based controller is a nonlinear firing angle controller, and the other two controller circuits are linear firing angle controllers. All operate at 60Hz controllers. With the aid of a SPICE simulation, the error of the ramp-comparator circuit has been minimized by means of an error blocking circuit added to block the discharging error of the ramp-comparator circuit. The ramp-comparator-based controller may have different errors for each channel. The phase-locked-loop controller consists of a ramp-comparator circuit and a phase-locked-loop circuit. It has the advantage of equal error per channel, and the error may be reduced by changing the free running frequency of the phase-locked-loop. The firing angle can be controlled linearly by changing the reference voltage of the ramp-comparators. For the phase-locked-loop based voltage controller, the possible range of the firing angle may be from 0° to 180° with much less than 1° error. The theoretical error formulas are derived, and the experimental results of the designed controllers are presented. The application of phase-locked-loop in three-phase inverter design is also discussed in this thesis.

CHAPTER 1

INTRODUCTION

What does research mean ?
When one cannot invent, one must at least improve.
- Fortune Cookie -

What does design mean ?
Design has no fixed form like water.
It depends on the practical situation and the economical constraint.
- Timmious Lee -

Most of the fundamental ideas of science are essentially simple, and may, as a rule, be expressed in a language comprehensible to everyone.
- Albert Einstein -

If you cannot—in the long run—tell everyone what you have been doing, your doing has been worthless.
- Erwin Schrödinger -

This thesis presents a discussion of the design and development of the firing circuits for the Power Electronics Laboratory of the Electrical Engineering Department at Montana State University. The Power Electronics Laboratory will provide the facilities for power electronics classes and for those who work on power electronics related research. The power electronics related research and classes at Montana State University involve mainly thyristorized systems such as three-phase AC to DC converters, AC voltage controllers (single phase and three-phase), DC to AC inverters, as well as simulations of those systems. Therefore, it is necessary to have a highly accurate and reliable firing controller for the thyristorized systems so that the students can conduct experiments in the Power Electronics Laboratory. Those who work on the simulations of the power electronic system can compare the exact experimental data with the simulated results. The firing circuits are designed mainly for educational purposes. Therefore, low cost, easy maintainability and linear firing angle control are the basic criteria of the designs. None of the designs in the current published papers to the author's knowledge have the capability to display and generate precise firing angles.

Several different approaches have been implemented [1-9]. However, all of them may not meet the above criteria. The main disadvantages of the circuit proposed by Le and Berg [1] are the non-linear response caused by the phase shifter and the complexity of the circuit. The phase shifter circuits suggested by Le and Berg [1] can be simplified to reduce the number of components. Even though the circuit uses non-linear control of the firing angle, it is worthwhile to have this circuit in the Power Electronics Laboratory in order to acquaint students with the operation of the phase shifter circuit and its advantages and disadvantages. The discussion of designing a phase-shifter-based three-phase firing angle controller is presented in

Chapter 2. The circuits proposed by Ilango, Krishnan, Subramanian and Sadasivan [2] and Simard and Rajagopalan [6] may cause nonlinearity in controlling the firing angle. The major disadvantages of the circuit proposed by Arockiasamy and Doraipandy [3] are :

1) A separate discharge circuit is needed.
2) Stabilized power supplies with +Vcc and -Vcc are required.
3) Because of the inherent finite rise time, the maximum frequency of operation is restricted.
4) It is difficult to control a three-phase rectifier bridge because of the tolerances of the components.
5) The circuit is very sensitive to the temperature.

The problems of the proposed circuit by Tang, Lu and Wu [4] are the cost and difficulty of maintenance. In addition to the disadvantages of [4], the circuit proposed by Mirbod and El-amawy [5] is very slow to respond, and it takes 200ms to track and lock on the input frequency. It is slower than one cycle. The fastest response of a phase-locked loop is to lock on the input frequency during the next cycle. A low order of linearity is the shortcoming of the circuit in Krishnan and Ramaswami [7]. The scheme proposed by Westinghouse [8] may be suitable only for a single phase firing circuit, and it is also not linear. In Sugandhi and Sugandhi [9] two different approaches, namely the ramp-comparator method and the relaxation oscillator method employing a UJT (unijunction transistor), are discussed. The main problem of the ramp-comparator method is that it has error terms due to the discharge of the charged capacitor. The major shortcoming of the relaxation oscillator method is that the total range of the control is only around 150°.

The error terms of the ramp-comparator method may be corrected by adding an error term blocking circuit. Therefore, the ramp-comparator method should be one of the best ways to control the firing angle linearly. The temperature dependence problem can be minimized by using a constant current source integrated circuit chip. The firing angle can be indicated directly on the digital voltmeter (DVM) by adding a subtractor to subtract the saturation voltage of the transistor. The discussion of designing a ramp-comparator-based three-phase firing angle controller is presented in Chapter 3. This circuit is designed for controlling single phase or three-phase output voltages. It can be used for controlling a DC to three-phase inverter. The phase-shifter-based three-phase firing circuit also has the same functions. By employing the combination of the ramp-comparartor circuit and the phase-locked loop (PLL) circuit, the circuit in Chapter 3 can be simplified. A PLL based firing circuit has the advantage of equidistant pulse firing. It can be used to control an AC to DC converter and a DC to three-phase inverter or a three-phase voltage controller by changing the conduction angle of the thyristors. The discussion of designing a PLL-based firing angle controller is presented in Chapter 4. The discussion and the conclusion of this thesis are presented in Chapter 5 and Chapter 6 respectively.

CHAPTER 2

PHASE-SHIFTER-BASED FIRING ANGLE CONTROLLER DESIGN

Introduction

This chapter is devoted to the study of the phase-shifter-based firing circuit for naturally commutated power electronic circuits, e.g. an AC voltage controller, a rectifier bridge and an inverter. The concept to develop the firing scheme has been reported in Le and Berg [1]. However, the circuit reported in Le and Berg [1] has component redundancy which makes the circuit cost ineffective. An attempt has been made to reduce the number of components needed to realize the circuit. It is shown that the same characteristics can be obtained for the circuit with a reduced number of components. Further, the complete design procedure of the phase-shifter firing circuit is reported. The experimental results are also reported to verify the validity of the circuit.

Basic Phase Shifter Circuit

A phase shifter is one of the most economical ways to control the firing angle of a three-phase thyristor bridge. In the paper by Le and Berg [1], the phase shifter is implemented by using three operational amplifiers. The original phase shifter of the paper is shown in Figure 1.

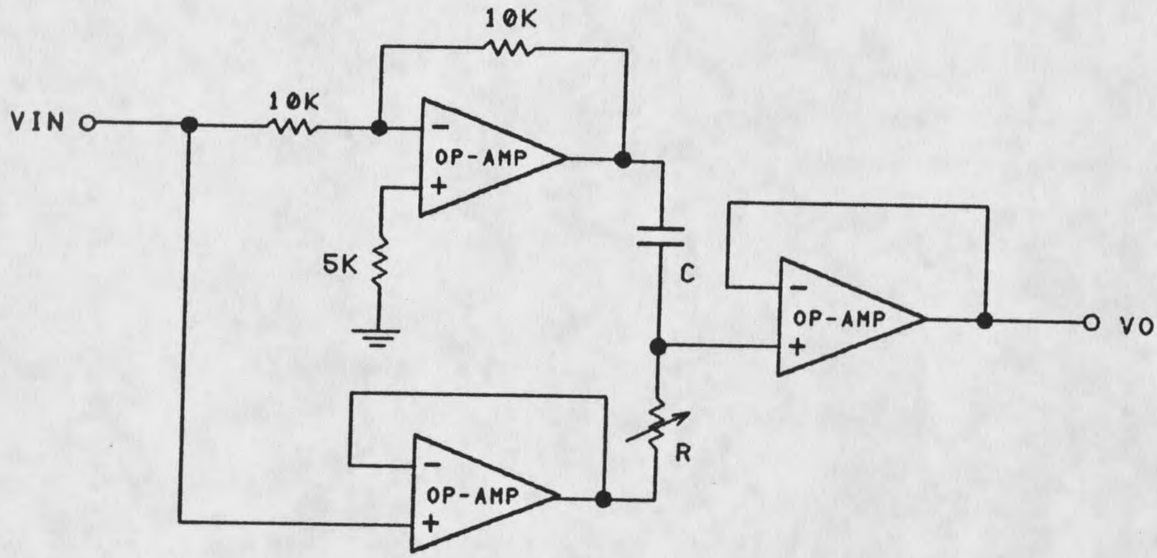

Figure 1. Phase shifter circuit from [1].

The phase shifter circuit has a gain of 1 and the phase angle θ of circuit can be written

$$\theta = -2 \arctan (WCR) \qquad (2.1)$$

where W is the input frequency in radians per second. The three operational amplifiers may be replaced by a single operational amplifier with exactly the same gain as well as the same phase shift function. The derivations of the gain and the phase shift function are shown in Appendix A. The phase shifter using one operational amplifier is shown in Figure 2. In equation (2.1), the phase angle θ will be zero if WCR is equal to zero and the phase angle θ will approach -180° if WCR approaches infinity. With a variable resistor of 1MΩ and a capacitor of 1μF, the phase angle θ can be adjusted from 0° to -179.7° at 60Hz(377radians/sec).

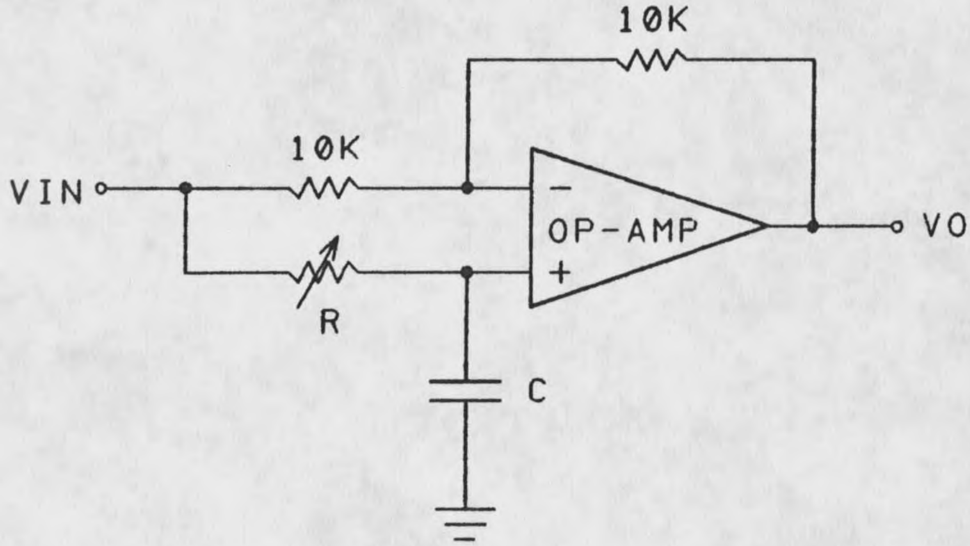

Figure 2. Single operational amplifier phase shifter

Application of Phase Shifter in Firing Circuit Design

Figure 3 shows a block diagram of a single phase control scheme which employs a phase shifter. In Figure 3 after the phase shifter circuit receives the input signal, it generates an output signal with a lagging phase angle as discussed in the previous section. This signal passes through a zero crossing detector stage where the sine wave is converted into a square wave. The square wave output signal is modulated by a 20kHz pulse signal using a two-input AND gate. After receiving the signal from the AND gate, the pulse driver drives a pulse transformer. The output signal of the pulse transformer is rectified and the rectified signal is used to trigger the thyristor with the

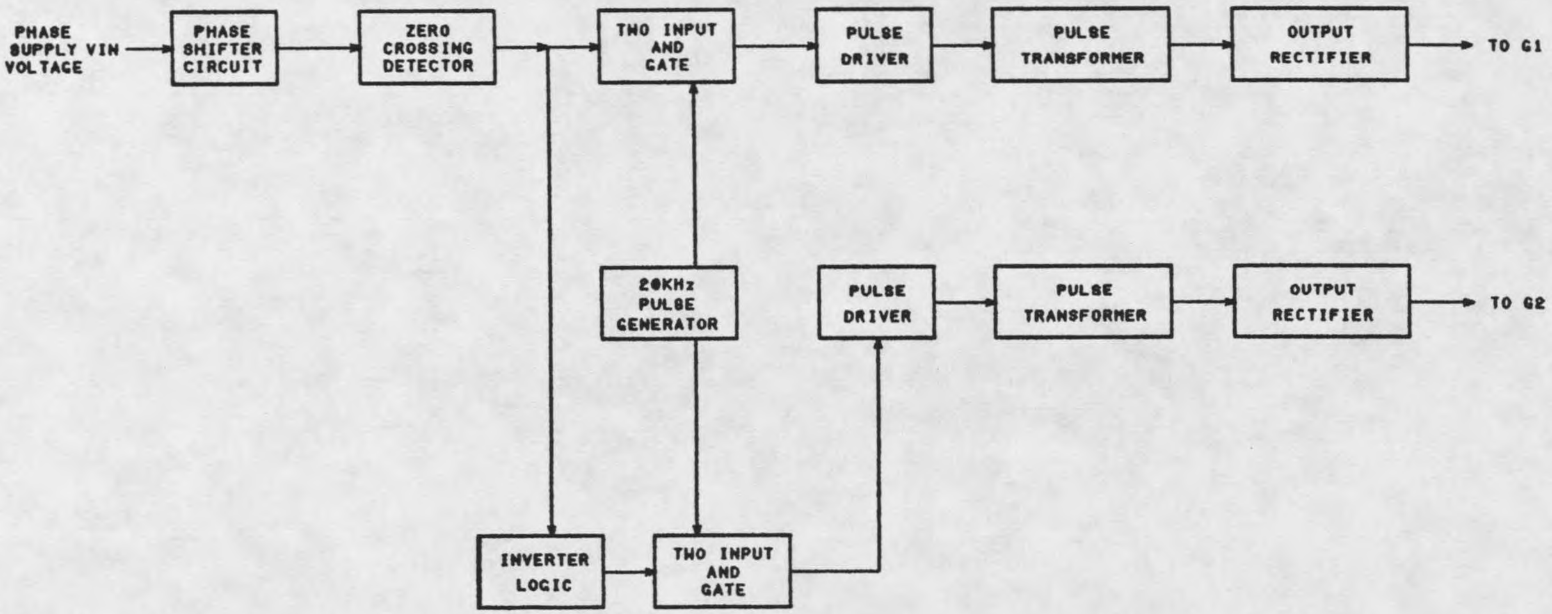

Figure 3. A block diagram of a single phase phase-shifter-based firing circuit.

firing angle range from 0° to 180°. In order to obtain the firing angle from 180° to 360°, an inverter is added to the output of the zero crossing detector; then the signal processing circuit is just like the one mentioned previously. The purpose of the pulse transformer is to isolate the pulse signals of the firing circuit because the pulse triggering signals of the firing circuit cannot have a common ground. Otherwise, the thyristorized control system may be damaged. The function of the pulse output signal, modulated by 20kHz, is to reduce the losses of the pulse transformer. The pulse transformer cannot be used in a low frequency application. How low the frequency can be is determined by the magnetic material of the pulse transformer. The lowest operating frequency of the commercial types of pulse transformers is typically 4kHz. The rectifier circuit is used to prevent the gate of the thyristor from mis-firing and to protect the pulse driver circuit in case the thyristor is damaged.

Phase-Shifter-Based Three-Phase Firing Circuit

Figure 4 shows a block diagram of a phase-shifter-based three-phase firing circuit. Three phase-shifters are employed in the circuit. One of them is used to control the the firing angle, and each of the others generates a 120° phase shift. In other words, the circuit acts as a three-phase generator. If the firing angle is adjusted, the output of each pulse circuit will trigger the thyristor

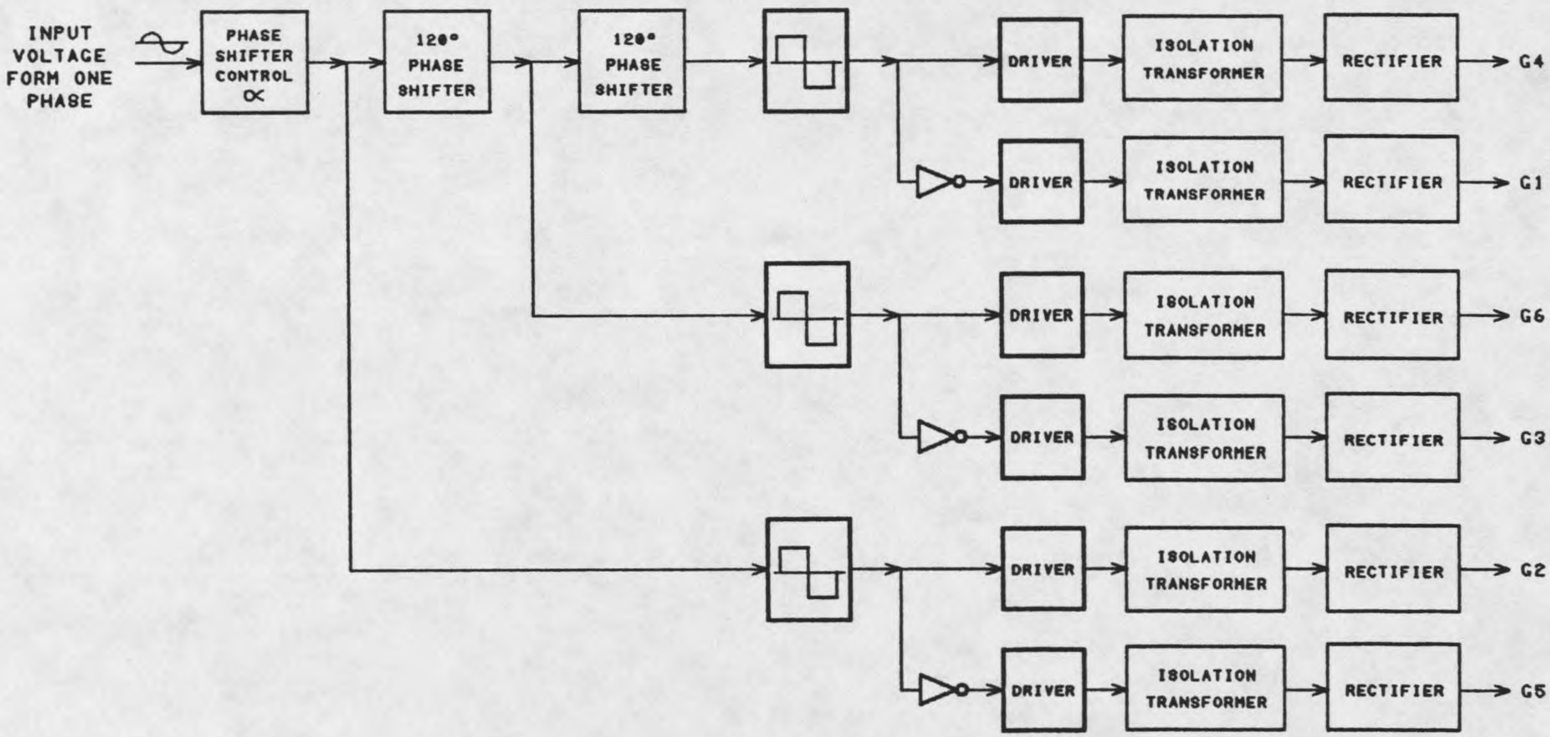

Figure 4. A block diagram of a three-phase phase-shifter-based firing circuit.