# PLL Based Firing Circuit for Three Phase Controlled Rectifier in Aircraft Landing Light

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***Abstract-*** Aircraft electrical components operate on many different voltages both AC and DC. Many aircraft power systems use 115 volts (V) AC at 400 hertz (Hz) or 28 volts DC. The most lighting services on aircrafts are powered by 28 V DC. They vary from 600 W for landing lights to few watts for minor internal illumination usages. The input voltage for the system is 115 V AC whereas the 600watts landing light uses only 28 V DC. It so needs to rectify the three-phase input AC voltage to DC voltage for the voltage requirement of the landing light. The theme of this paper is to design phase-locked-loop (PLL) based firing controller circuit for controlling the firing angle required. The PLL based firing controller circuit is linear firing angle controller. In PLL based firing angle controller circuit, 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. As ramp-comparator circuit and PLL circuit are involved in the controller circuit, it has the advantage of equal error per channel, and the error may be reduced by changing the free running frequency of PLL. The results of firing circuit are tested by PROTEUS software in this paper.

*Keywords*: alternating current, direct current, circuits, phase-locked-loop, landing light

## I. INTRODUCTION

Aircrafts are equipped with a variety of lights that are used for navigation, safety and to improve visibility during flight or when taxiing on the ground [4]. Lighting systems on aircrafts' are exterior lighting, interior lighting and emergency lighting. Exterior lighting system consists of landing lights, taxi lights, logo lights, wing illumination lights, service lights, position lights, anti-collision lights and strobe lights. The landing light is light for night landing. And it is located on wing leading edge or landing gear. The voltage rating that landing light use is 28 V DC or 115 V AC. Its power rating is 600 W. Past and present technologies include ordinary incandescent lamps, halogen lamps, various forms of arc lamps and discharge lamps and LED lamps. The airplanes have both transformer-rectifiers to turn the 400 Hz AC voltage into DC voltage for the 28 volts buses, and a static inverter to create the AC 400 Hz in case the aircraft power decreases up to the battery power. The aircraft battery offers a short-term power storage capability [1]. Most of aircrafts' electrical systems use a three-phase, 400 Hz, AC bus supplied by engine driven generators. However, most aircrafts' lighting systems use only 28 V DC. Due to aircraft generating power is 115 V, 400 Hz AC and the required voltage level for the landing light is 28 V DC, the input AC voltage must be converted into required DC output voltage.

In converting voltages from AC voltage to DC voltage, there are many electronic switching devices used for rectification mode. The most used switching devices are diodes, thyristors (SCRs), gateturn-off thyristors, power Darlington transistors, power MOSFETs, and insulated-gate bipolar transistors (IGBTs) [2]. Power semiconductor devices are the most important functional elements in all power conversion applications. In this paper, thyristor which is also known as silicon-controlled rectifier (SCR) is used as the switching device for controlled rectifier.

There are various methods for controlling the SCR by providing the pulses to the gate for the purpose of rectification AC to DC.In accordance with Tai-Ming Timmious Lee [3], the phase-locked-loop based firing circuit has the advantages over phase shifter based firing circuit and ramp comparator based firing circuit due to the following facts. The accuracy of the phase-locked-loop based firing circuit is very high if compare with the other circuits. Although the circuit complexity of phase-locked-loop based firing circuit is more complex, the error for each channel is extremely less than the others. And also the linearity of the phase-locked-loop based firing circuit is the best among these firing circuits. In this dissertation, there is detailed description and functioning of each block of phase-locked-loop-based firing angle controller circuit. The phase-locked-loop-based firing circuit is better for firing controlled thyristors at a constant, equidistant spacing. The maximum error that may be introduced in the equidistant spacing of the consecutive pulses can be shown to be 360º/N where N is a frequency multiplying factor.

## II. METHODOLOGY

### *A. Three-phase Six-pulse Bridge Controlled Rectifier*

Generators on most aircrafts produce 115 V, 400 Hz. Power generated from the generators is directly used without modification or is routed through transformers, rectifiers and inverters to change voltage or type of current. Most lighting system on aircrafts use 28 volts DC. For the voltage requirement of landing light which is 28 volts DC, the input AC voltage; 115 V, 400 Hz, needs to rectify. The steps for rectifying 115 V, 400 Hz AC to 28 volts DC are shown one by one in block diagrams of Fig.1.

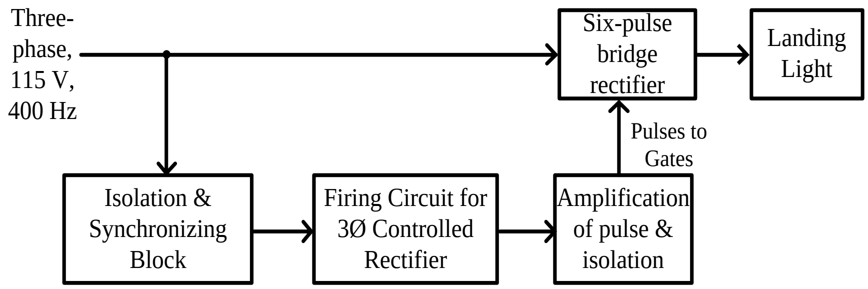


Figure 1.Three-phase Controlled Rectifier for Landing Light

Due to the difference in voltage levels of power circuit and firing controller circuit, the firing circuit must be isolated from the power circuit which has the high voltage system input of 115 V. And also for the purpose of producing synchronized firing angle for the rectifier used on high voltage system input, the low voltage input for the firing circuit must also be synchronized with the high voltage input of power circuit.And then the output voltage from the firing circuit is not high enough to trigger SCR used in bridge rectifier so that the amplification of this voltage is needed and so does isolation between power circuit and firing circuit. With the help of step-down transformer, the input AC supply voltage is stepped down from 115 V to 8 V which will be used for the gate-pulse signal firing circuit.

### *B. Firing Circuit for Three-phase Controlled Rectifier Using Phase-Locked-Loop Technique*

The block diagram of a three-phase phase-locked- loop based firing controller circuit is illustrated in Fig.2. The input voltage for the firing circuit is low level voltage which is the secondary low voltage of the step-down transformer. After passing the zero-crossing detector circuit, the input sine-wave signal is inversely converted into the square-wave signal and then is fed to the ramp-generator circuit as the input signal. The output signal of the ramp-generator will be compared with the DC reference voltage which can be set constantly the voltage value for the firing angle. The two output signals from the two ramp-comparators are fed to the AND gates for the purpose of error blocking. The error blocking circuit is built to block the discharging error of the capacitor in the ramp-generator. The S-R flip-flop is used to set 180º phase shift of the two input signals of it.

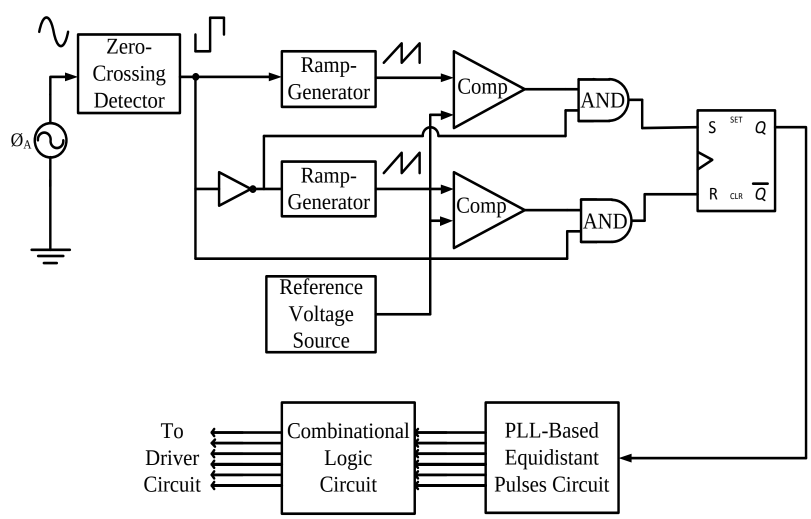


Figure 2. A Block Diagram of Three-phase Phase-Locked-Loop-Based Firing Controller

And then the phase-locked-loop circuit is driven by the output signal of the S-R flip-flop. The range of most of the existing firing circuits may not cover from 0°to 180°. The firing circuit can be adjusted from 0° to 175° so that the error of the firing circuit is 5°. By adjusting free running frequency to shift the phase angle of the PLL output, the firing circuit can be adjusted from 2.5° to 177.5° so that the error of the firing circuit is 2.5°. Therefore the error of the linear firing circuit may be reduced by half by changing the free running frequency of the PLL chip. Actually, the PLL-based firing circuit may be adjusted from 0° to 180° with less than a 1° error. This error is caused mainly by the modulated frequency of the pulse driver and the turn-on time delay of the thyristor. All the error terms of the input stages can be corrected by changing the free running frequency of the PLL chip to shift the phase of the output frequency. The overall circuit diagram is shown in detail in Fig.3.

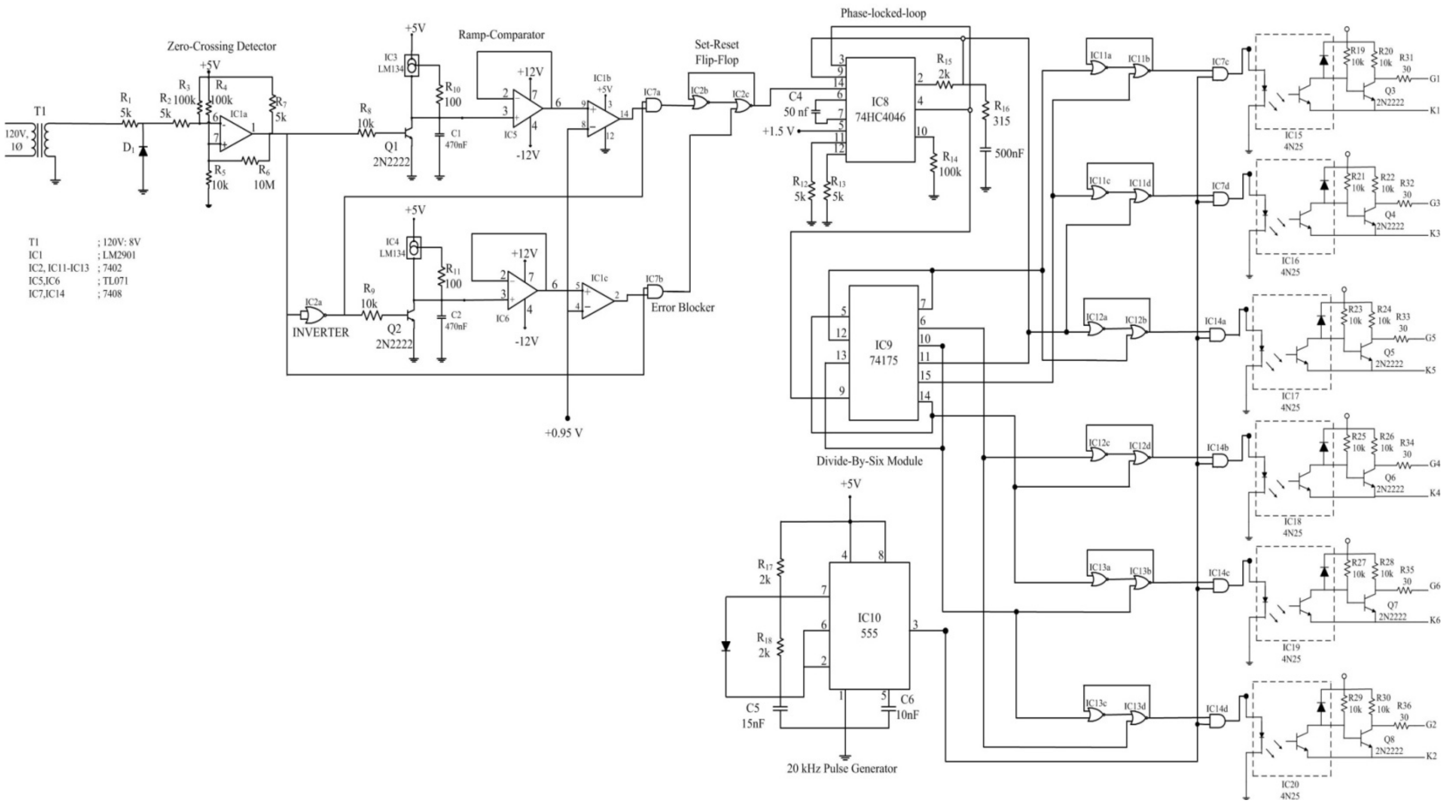


Figure 3. Three-phase Phase-locked –loop Based Firing Circuit

## III. DESIGN CONSIDERATION AND SIMULATION RESULTS

### *A. Zero-Crossing Detector*

It is designed for the usein level detection, low-level sensing and memory applications in consumer and automotive and industrial electronic application. In this project, it generates output when the input, which is the output sin-wave voltage signal of the step-down transformer, crosses a reference point; in this case zero volts or ground.LM 2901 is used for realizing Zero-Crossing Detector.
The values of each component for the zero-crossing detector are selected according to the following equations:

$$R_1 + R_2 < 10k\Omega \qquad \text{Eq (1)}$$

$$R_1 + R_2 \approx R_5 \qquad \text{Eq (2)}$$

$$R_5 \leq R_4/10 \qquad \text{Eq (3)}$$

$$R_3 = R_4 \qquad \text{Eq (4)}$$

$$R_6 \gg R_4\, , R_6 \gg R_5 \qquad \text{Eq (5)}$$

$$R_7 \approx R_2 \qquad \text{Eq (6)}$$

By choosing the value of resistor $R_5$ about $10\,k\Omega$, the values of resistors, $R_1$ and $R_2$, will become $5\,k\Omega$. And according to the Equations 3 and 4, the values of resistors $R_3$ and $R_4$ are calculated and the result is $100\,k\Omega$. Due to Equation 5, the value of resistor $R_6$ is selected as $10\,M\Omega$. And the value of the resistor $R_7$ is chosen as $5\,k\Omega$ according to Equation 6. The comparators in LM 2901 IC chip are designed to operate from a single power supply over a wide range of voltages. . In the paper, $5\,V$ single power supply is used for the zero-crossing detector. The simulation results for the zero-crossing detector circuits with the input ac signal and output inverse square-wave are shown in Fig.4.

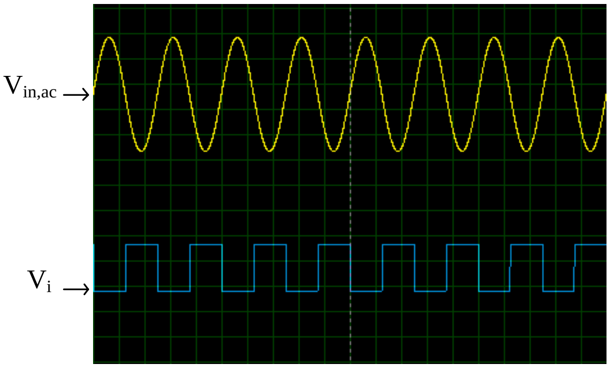


Figure 4 Input and Output Voltage Signals of Zero-Crossing Detector

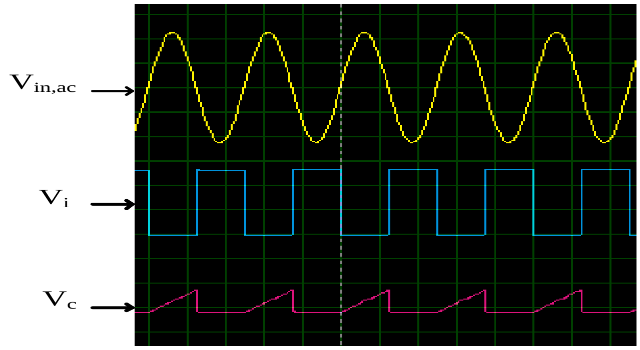


Figure 5 Output Voltage Waveforms of Zero-Crossing Detector and Ramp-Generator

*B. Ramp-Comparator Circuit*

A ramp-comparator circuit is composed of two elements, a ramp-generator and a comparator. For the ramp-comparator circuit, the output voltage signal of the zero-crossing detector is used as the input signal of the ramp-comparator. In ramp-generator circuit, LM 134 is used as the three-terminal adjustable current source and 2N2222 transistor is used as the switching transistor. And the values of each component of the ramp-generator are calculated as the following equation;

$$V_C = \int_0^t \frac{I_s}{C}\, dt \qquad \text{Eq (7)}$$

By assuming the voltage $V_c$ for the maximum value about 1.5 volts and the capacitor C is about $470\,nF$ whereas the time $t$ is the upper case value of about $1.25\,ms$ for the $400\,Hz$ frequency, the result of current $I_s$ is calculated as $0.564\,mA$. And according to the reference [7], the value of $R_{set}$ is calculated as $120\,\Omega$ but it is chosen about $100\,\Omega$ in this paper. And the simulation results for the ramp-generator and also zero-crossing detector circuit are shown in Fig 5.

TL 071 IC chip is used for realizing buffer amplifier behind the ramp-generator circuit, which has wide common mode (up to $V_{CC+}$ ) and differential voltage range, low input bias and offset current and high slew rate : $16V/\mu s$. As the buffer amplifier, it has a unity gain and very high input impedance. And it is also essentially an impedance transformer. The simulation results of ramp-generator and unity gain buffer amplifier are shown in Fig 6.

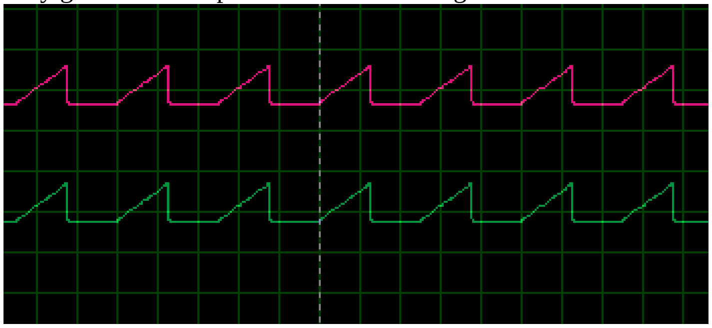

Figure 6 Output Voltage Waveforms of Ramp-Generator and Buffer Amplifier

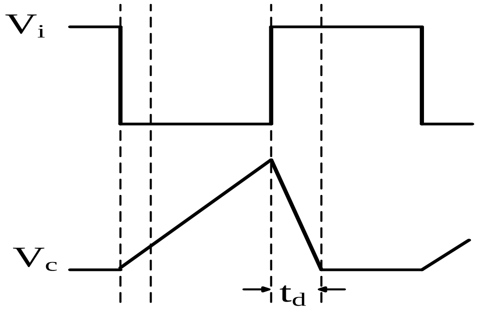


Figure 7 The Pulse Response of the Ramp-Generator

*C. Error Blocking Circuit*

One major problem is caused by discharging the capacitor of the ramp generator. In Fig 7, $t_d$ is the error term caused by the discharging error of the ramp-generator. As a result, $V_0$ in Fig 7 contains error. One thing which can be done to avoid the discharging error is to add an additional discharging circuit to the output of the ramp-generator.

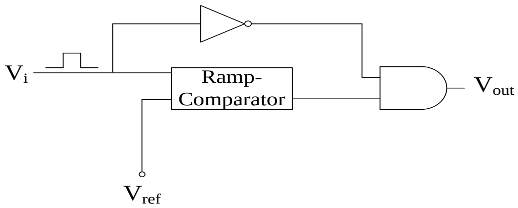


Fig 8 Error Blocking Circuit

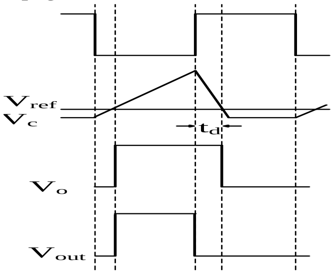


Figure 9 Pulses Response of the Error Blocking Circuit

This addition can be minimized $t_d$. However, it is impossible to reduce $t_d$ to zero. The technique called error blocking can be used to block the discharging error is shown in Fig 8. When the input signal of the ramp generator is low, the linear ramp waveform is generated. An inverter and an AND gate are added to the circuit. If the input signal, $V_i$, goes low, the output of the inverter will go high. If $V_c$ is greater than $V_{ref}$ in ramp-generator circuit, $V_{out}$ will go high. No matter whether the ramp-comparator output is high or low if $V_i$ goes high, $V_{out}$ will go low.The simulation results for the ramp-comparator circuit and error-blocking are as shown in Fig 10. To convert the variable width pulses obtain from comparator outputs to get 180° width pulse, the S-R Flip Flop is used. The simulation results for the positive edge triggered S-R Flip-Flops are shown in Fig 11.


Figure 10 Output Voltages Waveforms of Error Blocking Circuit

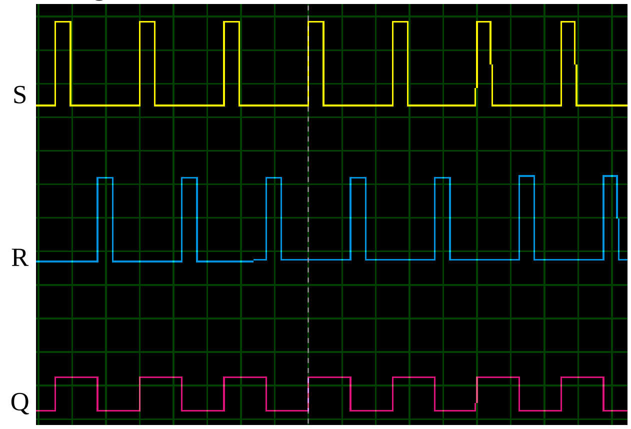


Figure 11 Output Voltage Waveforms of Positive Edge Triggered S-R Flip-Flop

*D. Phase-locked-loop*

A phase-locked-loop is commonly used in motor control, frequency synthesizers and radio receivers. In designing a thyristorized three-phase AC to DC converter, a phase-locked-loop technique is usually employed to generate equidistant spacing of six consecutive pulses for triggering six thyristors. The basic principle of the equidistant pulses scheme is simplified into a scheme as shown in Fig 12. In Fig 11, when the phase detector receives the input frequency, $f_i$, the phase detector outputs a phase difference signal, $f_d$, by comparing the signals of $f_i$ and $f_c$. After the low pass filter receives the output signals from the phase detector, the low pass filter integrates the phase difference signal and outputs a DC signal. This DC signal can control the output frequency of the voltage controlled oscillator, VCO. Then the output signal of the VCO is divided by six and the resulting signal is the $f_c$. The output logic signals of the divide-by-six module can be used to drive the driver circuit. In other words, the circuit is shown in Fig 12 works like a frequency multiplier. A divide-by-six module can be implemented by using three flip-flops.

In this paper, 74HC4046 IC chip is used for the phase-locked-loop circuit, and TTL 74175 IC chip is used for divide-by-six module. The simulation result for phase-locked-loop circuit using 74HC4046 IC chip is shown in Fig 13.

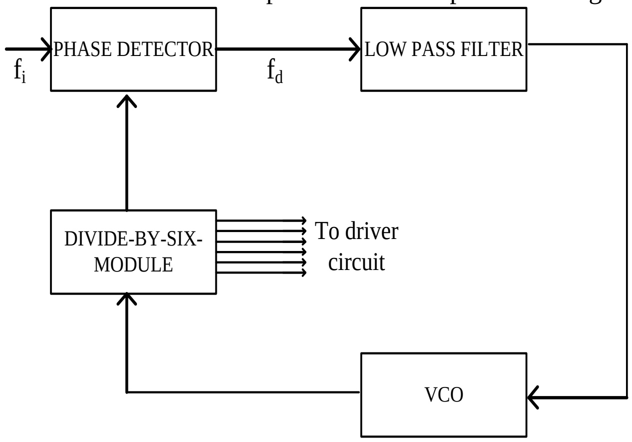


Figure 12 A Block Diagram of Equidistant Pulses Scheme

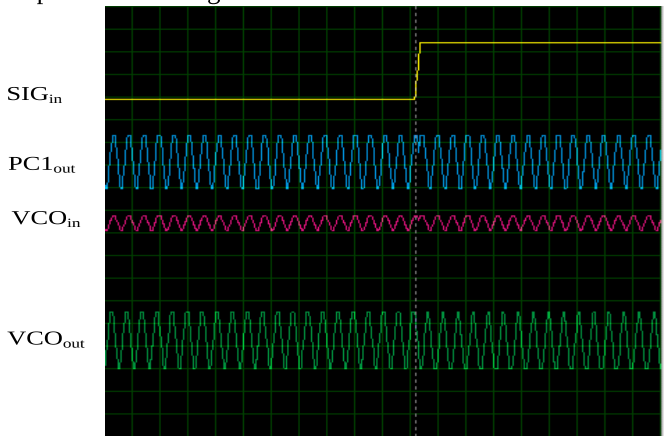


Figure 13 Outputs Waveforms of Phase-Locked-Loop 74HC4046 Chip

*E.* High Frequency Waves

Pulse gating of thyristor is not suitable for RL loads, and this difficulty can be overcome by using continuous gating. However, continuous gating may lead to increase thyristor losses and distortion of output pulse. So, a pulse train generated by modulating the pulse gate at high frequency is used to trigger thyristor. This high frequency wave is known as carrier wave and is generated by 555 timer. AND operation is performed between the S-R flip-flop outputs and carrier waves so that pulses required for triggering the thyristor called firing pulses or gate pulses are obtained. The simulation results of AND gate for the positive polarity and negative polarities are shown in Fig 14.

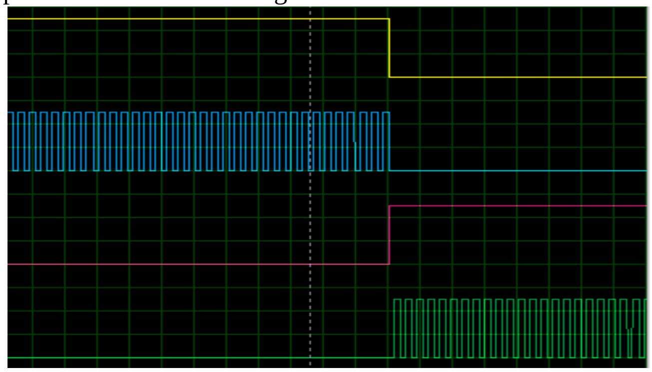

Figure 14 Simulation Results for AND Gates

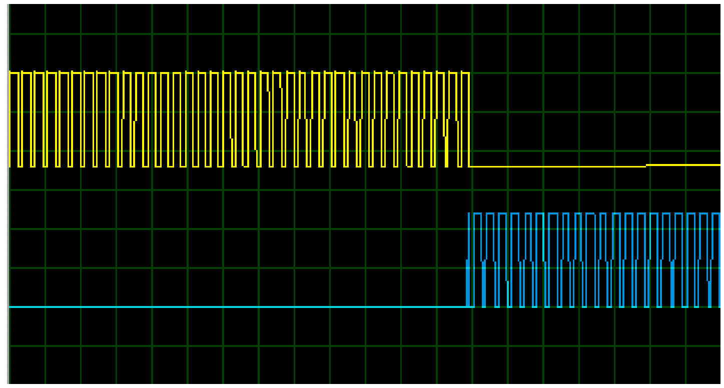

Figure 15 Final Pulses for Gate Terminals of Thyristors

### *F.* Amplification of Pulses and Isolation

Outputs from the AND gates cannot be connected directly to between gates and cathodes of thyristors because the outputs will not be able to supply the necessary current required by the gate circuit of thyristor. Apart from this, isolation between the control circuit and power circuit is also required. Therefore, with the help of phototransistor-based optocoupler circuit, these two objectives of strengthening the pulse and providing the isolation are met. For the gate circuit voltage requirement of thyristors, the gate-pulse voltages for the thyristors are amplified by supplying about 12 V to the transistor of phototransistor-based optocoupler circuit.

In this paper, the 4N25 phototransistor-based optocoupler is used. Final pulses after isolation and amplification using phototransistor-based optocoupler circuit are shown inFig 15.

## IV. CONCLUSION

In the ramp generator circuit, overdriving will result in a low saturation voltage of collector to emitter in the transistor. It helps to reduce the error of the ramp generator circuit. The error blocking circuit helps to block the discharging error of the ramp generator. The phase-locked-loop-based firing controller has two ramp generators. Therefore, the procedures of calibration are less complex. The free running frequency of the PLL chip can be adjusted to reduce the error of the phase-locked-loop-based firing controller. All the error terms of the input stages can be corrected by changing the free running frequency of the PLL chip to shift the phase of the output frequency. According to the final gate pulse signals of the proposed firing circuit are high enough to drive the gate voltage of thyristor on the six-pulse bridge controlled rectifier, the proposed firing circuit is good enough to use in the rectification of input $115\,V$ AC system to the required $25\,V$ DC voltage for the 600 W landing lights.

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