



LED Timing Light Upgrade for Synchronous Machines Laboratory Equipment

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LED Timing Light

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Abstract

The purpose of this project is to develop a timing light circuit capable of using a light emitting diode. With the incandescent light bulb no longer being produced, there is a demand for a timing light capable of using an LED. The trouble with using an LED in place of an incandescent bulb is its inability to emit light when exposed to the low or negative voltages. This issue is addressed using a full wave rectifier and introducing a biasing voltage. The LED timing light will have the same behavior as the conventional timing light. The timing light increases in brightness as the phase angle between two sinusoidal voltage sources deviates from zero degrees. For example, it can be used to ensure a generator and power grid frequencies and timing are in sync before being electrically connected. This LED timing light was developed for an energy systems lab where the lights are used to synchronize a three phase synchronous generator to a large stable system which is essential in ensuring the stability of any power grid.

Introduction

A conventional timing light shown in Figure 1 uses a halogen light to determine if the voltages sources, of approximately equal amplitude, are in phase with each other. When the voltage from the generator is in phase with the power grid, the current through the light is zero. The current is at its maximum when ϕ , the phase angle is between the two sources, is 180 degrees.

The phase angle in radians shown in equation (1) is a function of t , the time delay between sources, and ω , the radian frequency.

$$\phi = t \cdot \omega \quad (1)$$

The conventional timing light is out of date because halogen lights are no longer manufactured due to their inefficiency. This brings a demand for a timing light circuit capable of using an LED. The issue with using an LED is its inability to allow current flow in both directions or when the voltage falls below the forward bias voltage drop V_{fb} . The new LED timing light circuit should

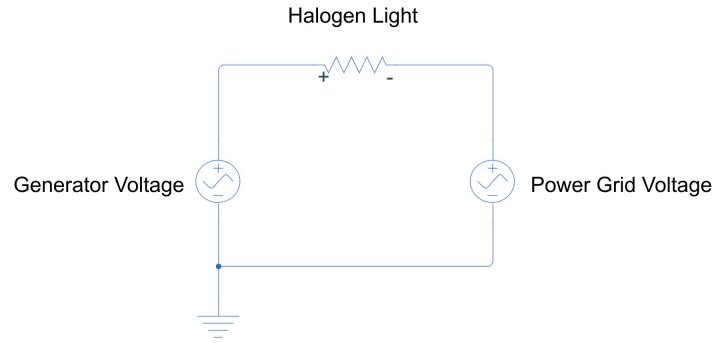


Figure 1: Conventional single phase timing light circuit

behave the same as the conventional timing light where the current through the LED peaks when the phase is equal to 180 degrees.

Methods

First looking at a single phase model, the two main issues with using LED are:

- current can only flow in one direction
- current can only flow when the voltage across the LED V_{LED} is greater than V_{fb}

In order to keep the voltage above V_{fb} a biasing DC voltage source equal to V_{fb} is added. Because current only flows in one direction through the LED the voltage across the LED must remain positive. This is done using a full wave rectifier shown in Figure 2 with the biasing DC voltage source, V_{DC} .

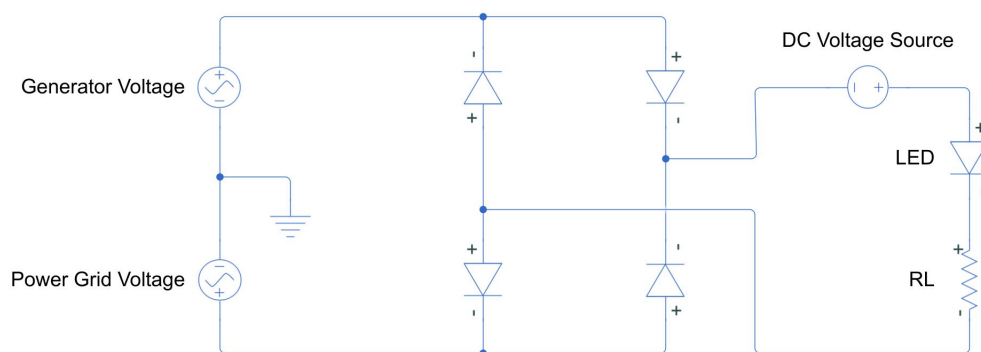


Figure 2: LED timing light circuit

The LED is the brightest when current is at its maximum which occurs when the phase angle is 180 degrees. The maximum current is given by equation (2), and the minimum current is given by

equation (3). V_{grid} is the power grid line-neutral rms voltage (V), and V_{gen} is the generator line-neutral rms voltage (Vr). V_d is the forward bias voltage of the diodes used in the rectifier circuit. R_L is the resistor in series with the LED.

$$I_{max} = \frac{\sqrt{2} \cdot V_{grid} + \sqrt{2} \cdot V_{gen} - 2 \cdot V_d + V_{DC} - V_{fb}}{R_L} \quad (2)$$

$$I_{min} = \frac{V_{DC} - V_{fb}}{R_L} \quad (3)$$

The DC voltage is added using a 3.3 V voltage regulator which can only keep the voltage stable when its current is positive. It is placed in series with the LED with a resistor R_L which is used to limit the current through the LED. The voltage regulator needs an input voltage between 5 V and 24 V which is provided by the power grid. Voltage from the power grid can be used to supply power to the regulator by using a full wave rectifier, and a voltage divider to reduce the voltage to be within range. The resistor values need to be chosen appropriately considering the voltage regulator's input voltage will decrease as the input current increases. This method is very inefficient due to the power loss in each resistor. An alternative to this would be to use a USB power supply to supply 5 V to the voltage regulator shown in Figure 3.

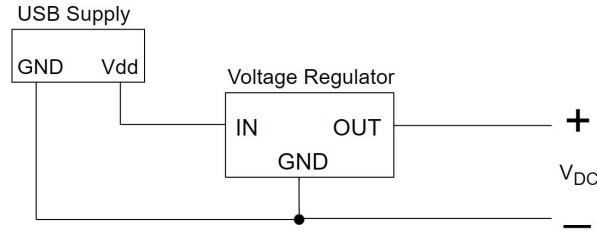


Figure 3: DC biasing voltage using voltage regulator

The hardware used for the LED timing light gives the following parameters:

- $V_d = 1.3 \text{ V}$
- $V_{DC} = 3.3 \text{ V}$
- $V_{fb} = 3.3 \text{ V}$
- $R_L = 36 \text{ k}\Omega$

There are two major concerns when choosing hardware for this circuit. The first is to ensure the diodes used in the voltage rectifier can handle a large enough reverse bias voltage, V_{RB} . The second is to ensure the load resistor's power rating, P_L is large enough to handle the maximum current. This circuit may be used to synchronize generator and power grid line-line rms voltages of up to 240 V. By increasing the voltage by a factor of two, V_{RB} will also increase by a factor of two, and P_L will increase by a factor of four. It is also important to verify that the LED being used has a forward bias voltage equal to V_{DC} .

Using 120 V for both the generator and power grid line-line voltage the maximum current through the LED is about 9 mA and the minimum current is 0 mA shown in Figure 4. The full 360 degree cycle is shown in Figure 5 using two sources of equal magnitude with slightly different frequencies.

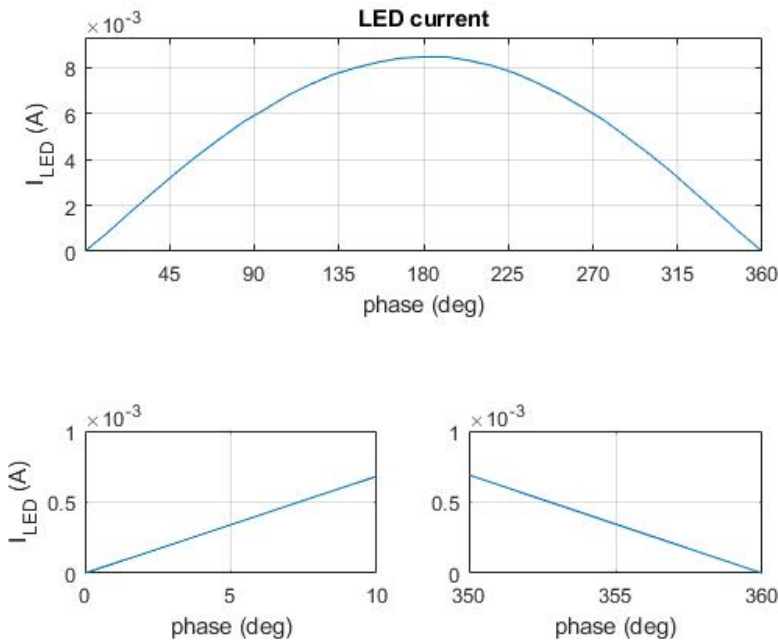


Figure 4: Peak LED current vs phase angle

In the case of a three phase system shown in Figure 6, the neutral line from the generator and power grid need to be connected, providing a common ground for the circuit. The three phase circuit also used three DC biasing voltages which used three separate voltage regulators. Because the regulators must not have a common ground, a separate USB power supply is used for each voltage regulator. This will prevent any current between lines. The final three phase circuit utilized four resistors in place of R_L shown in Figure 7 and on the printed circuit board layout in Figure 8. The use of multiple resistors will reduce the power absorbed by any one resistor. This circuit will be used in the lab at the University of Idaho to synchronize any two three phase circuits with up to 240 V line-line.

Results

The light emitted from the LED increases as the phase between the two voltage sources deviates from zero. The light emitted is represented by the current shown in Figure 9, which matches the behavior shown in the simulation. The full 360 degree cycle is shown using two sources of equal magnitude with different frequencies. The light emitted from the LED timing light circuit has more of a true sinusoidal characteristic than the conventional timing light. This is mostly due to the resistance of halogen light being highly affected by temperature.

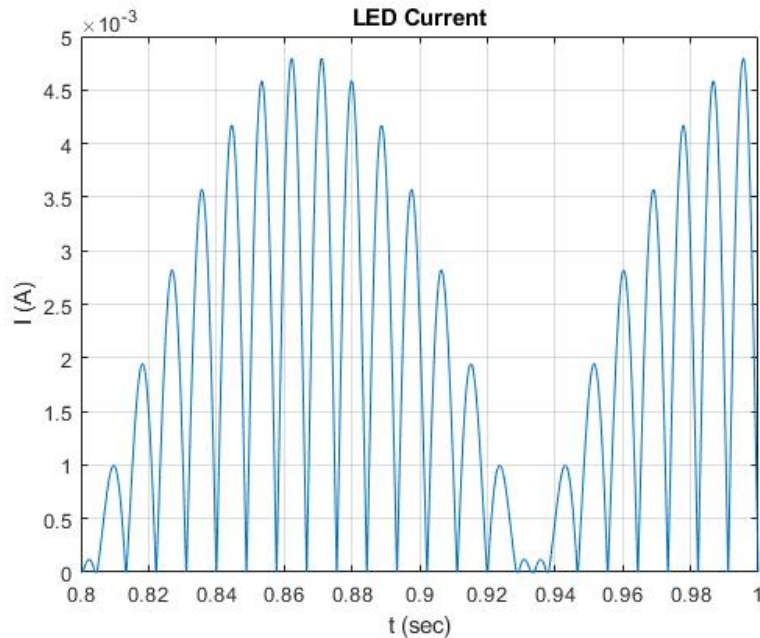


Figure 5: LED current simulation using two voltage sources of equal magnitude with frequencies of $f_1 = 60\text{Hz}$ and $f_2 = 52.5\text{Hz}$.

Assessment

Timing lights were originally designed into this laboratory's benches in 1989. They soon proved to be one of the most simple, the most insightful, and the most popular instruments that students use in an AC power laboratory at this university. Their primary focus in this Energy Systems II lab is for the synchronization between an AC generator and the local power grid. When federal legislation made their incandescent light bulbs obsolete in 2014, a replacement instrument design became necessary. The original instrument itself was so effective that there was never any question whether its format should be retained for educational purposes. The new design using LEDs duplicates the appearance of the incumbent successful design. The new design improves the "dead time" problem, the instrument's time interval where the light indication was too dim to see. Depending on ruggedness, which will be proven over the upcoming several years, this new design meets the educational objectives as well as its successful predecessor.

Conclusion

The circuit presented in this paper replaces an incandescent measurement unit to indicate a phase error between two alternating voltage sources. Its purpose is to enable synchronization between the same sources. A replacement unit based on light-emitting diodes (LEDs) was designed to perform the same indicator functions. It was successfully simulated for three phase sources and experimentally verified for voltages up to 240 Volts rms, 60 Hertz. A rugged printed circuit board encapsulates the design for inclusion inside incumbent laboratory benches.

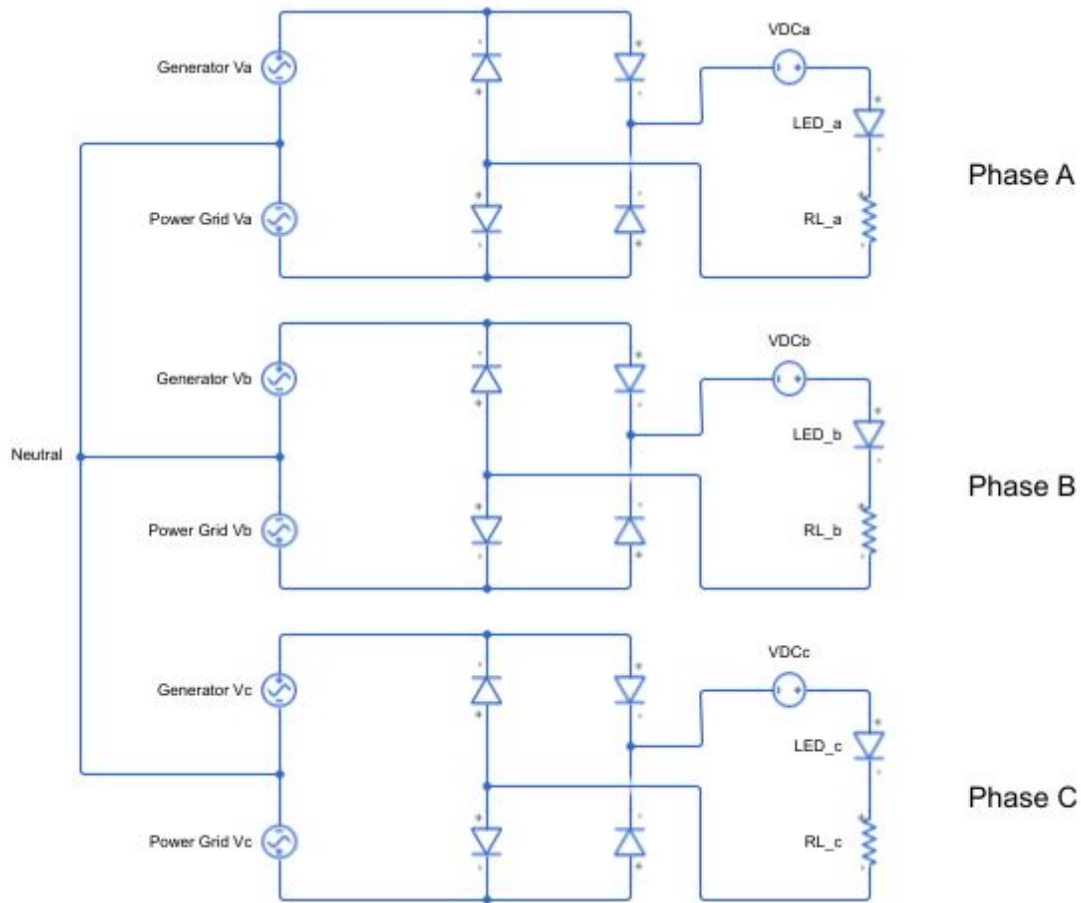


Figure 6: 3 phase LED timing light circuit

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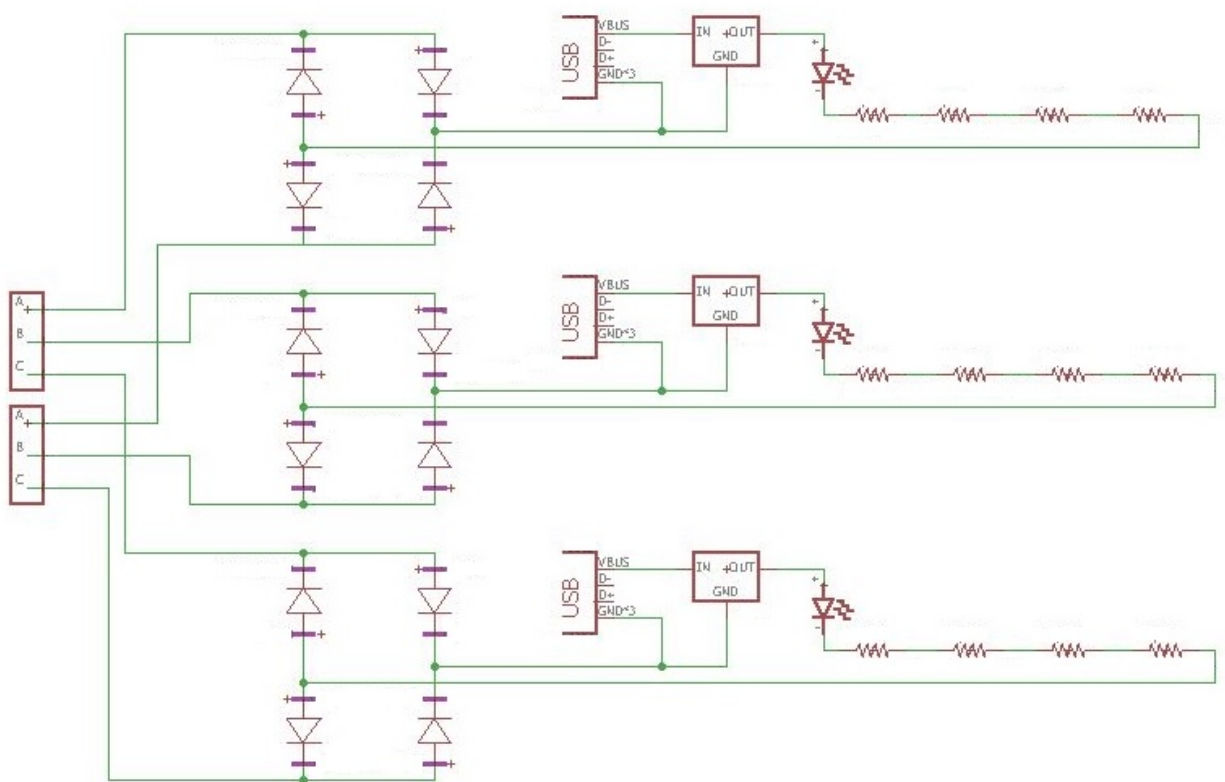


Figure 7: Three phase PCB schematic

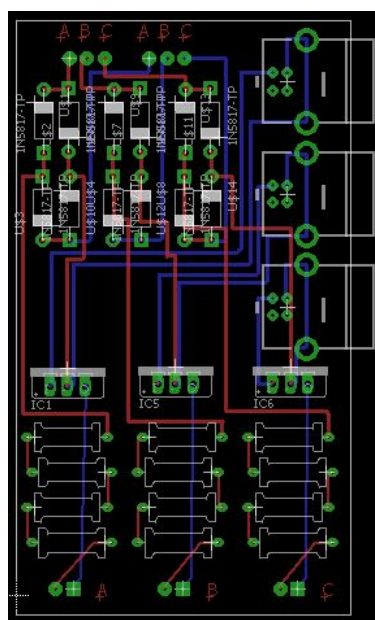


Figure 8: Printed circuit board layout: 8.5 cm x 5 cm

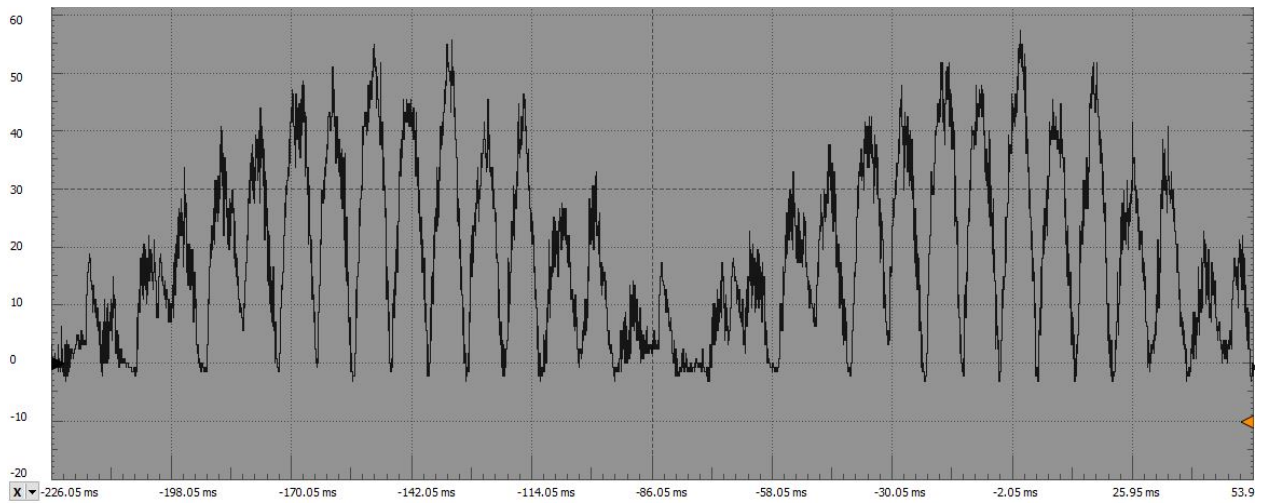


Figure 9: LED current using two sources of equal magnitude with frequencies of $f_1 = 60\text{Hz}$ and $f_2 = 52.5\text{Hz}$. The current in Amperes represented on the y-axis is four orders of magnitude higher than the actual current.